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Post-Flashover Fires in Shipboard Compartments Aboard Ex-USS SHADWELL: Phase VI — Boundary and Compartment Cooling

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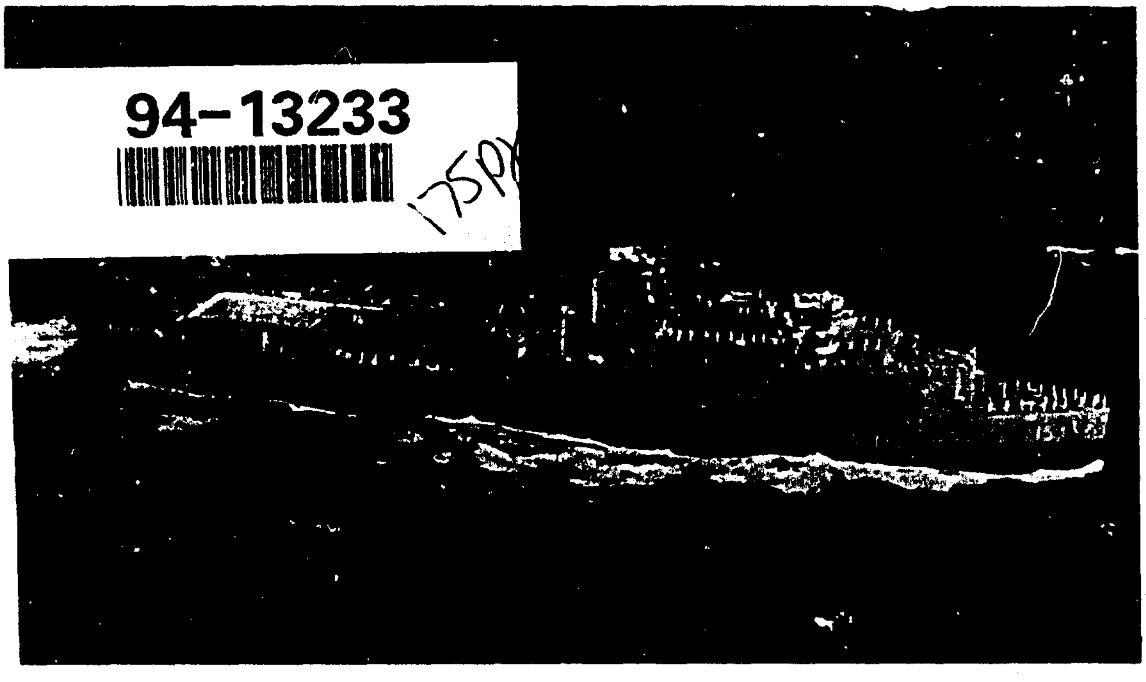

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13. ABSTRACT *(Maximum 200 words)*

Boundary and compartment cooling tests were conducted on the NRL fire research vessel, ex-USS SHADWELL. These tests were part of a series of tests under the Internal Ship Conflagration Control project.

A deck assembly was exposed to a post-flashover fire exposure for 20 minutes. After this exposure, the deck was cooled using manual firefighting equipment. This equipment included standard Navy firefighting nozzles (variable steam and all purpose), a small diameter hose and nozzle, and a water motor fan equipped with an experimental water mister. Cooling of the deck was accomplished using both a vertical and horizontal approach. Other variables included the personal protection worn by the firefighters and venting of steam created by boundary cooling.

The standard Navy equipment was effective in cooling boundaries. The small diameter hose and water mister were effective for compartment cooling when used in a horizontal approach. Steam burns occurred to protective clothing "weak links," including at the hands, neck, and feet. In particular, issues involving firefighter's gloves were identified.

The times firefighters could stay in the fire area was a function of protective clothing and venting of steam away from the personnel. Personnel improved their performance time by rotating out of the fire area before they were totally exhausted. Based on these tests, improvements to standard Navy firefighting doctrine, tactics, and equipment were recommended.

14. SUBJECT TERMS

Boundary cooling	Water steam	Post-flashover fires
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Post-flashover Fires in Shipboard
Compartments Aboard ex-USS SHADWELL:
Phase VI – Boundary and Compartment Cooling

1.0 BACKGROUND

The Internal Ship Conflagration Control (ISCC) program was initiated to address issues raised by the missile-induced fire on USS STARK. The overall objectives of the program were to develop guidance to the Fleet on the control of vertical fire spread and develop concepts for new ship design.

There were a number of aspects to the project. Preliminary testing at the Naval Research Laboratory (NRL) Chesapeake Beach Detachment (CBD) was performed to "design" a test fire [1]. The fire was intended to simulate the post-flashover fire conditions in a shipboard compartment following a propellant burn. Preliminary testing at NRL CBD also provided initial estimates of the effects of boundary cooling [2]. In this series of fire tests, cooling techniques were evaluated in simulated shipboard compartments. The compartments were steel cubes, 2.4 x 2.4 x 2.4 m (8 x 8 x 8 ft), arranged such that the fire compartment was in the center with two cubes on either side and one compartment directly overhead. The fire threat simulated instant flashover of the fire compartment. Both manual and installed water spray nozzles were evaluated for cooling efficiency.

It was found that a water application rate of 2.04 Lpm/m^2 (0.05 gpm/ft^2) was the minimum for cooling surface temperatures of both horizontal and vertical boundaries to 100°C (212°F). The temperature of the fire compartment was not reduced by aggressively cooling (using high application rates) the fire compartment boundaries as long as the fire remained burning. At application rates of 2.04 Lpm/m^2 (0.05 gpm/ft^2) or above, cooling of horizontal decks was independent of application technique. Vertical boundary cooling was strongly dependent on application technique. Maximum cooling efficiency was achieved when water was applied in sheets or continuous sprays tangentially to the heated surfaces. Nozzles producing a conical shaped water spray pattern applied perpendicular to the surface provided inadequate cooling at low application rates, but improved with increased application rates. The higher application rate was required due to the water droplets (streams) bouncing off the heated surface. Water from fine atomizing nozzles applied perpendicular to the heated surface proved to be inadequate for cooling of steel bulkheads. The fine drops lacked the needed momentum to penetrate the thermal updraft of stream and hot gases to adequately impact the heated surface. Water was found to be more efficient at removing heat energy when wall surface temperatures were between 100° - 250°C (212°-482°F), i.e., in the Leidenfront Transition region.

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At low application rates, only the front surface of a bulkhead was cooled. A minimum amount of steam was observed during these tests. At high application rates, both the front and back surfaces of the boundary were cooled, and significant amounts of steam were produced. The increased stream production was attributed to the ability to remove the heat stored in the steel plate.

Based on these preliminary CBD findings, techniques for effectively cooling boundaries to prevent fire spread were developed for the standard Navy 360 Lpm (95 gpm) vari-nozzle. It was recommended that, after wetting the combustibles in the compartment, the boundary should be aggressively cooled by sweeping with a 30° fog pattern for two and one-half minutes or until conditions become untenable for the firefighter. Short 15-second bursts every three minutes were thought to be more than adequate to keep the bulkhead cool and prevent fire spread. Based on the findings and recommendations from the CBD tests, the then-current version of NSTM 555, the Navy's technical manual on firefighting doctrine, tactics, and procedures was revised to recommend boundary cooling at a rate of 15 seconds every minute [3].

Subsequently, the post-flashover fires developed at NRL CBD were scaled-up on ex-USS SHADWELL. This is the NRL fire research platform used to evaluate materials, equipment, and procedures for the Navy. A complete description of the test platform is contained in Reference [4]. The cooling tests, performed in the time frame of 6 February 1991 to 4 April 1991, described in this report served as a precursor to Fleet Doctrine Evaluation tests, where expert Navy firefighters gather on the SHADWELL to evaluate advanced firefighting doctrine, tactics, and procedures. The boundary and compartment cooling tests were also conducted concurrently with testing and evaluation of the water motor driven portable blower [5]. This device was introduced to the Fleet after the USS STARK fire to provide increased desmoking and ventilating capability.

2.0 OBJECTIVE AND SCOPE

The objective of this test series was to evaluate alternative equipment, tactics, and techniques for boundary and compartment cooling. The primary emphasis was on the prevention of vertical fire spread using existing shipboard equipment and readily available commercial devices/materials. The baseline objective was the containment of a large post-flashover fire or "mass conflagration." No direct extinguishing action was taken on the fire. The philosophy for evaluating new equipment was that it had to have multiple uses/applications or it must provide significant improvements over existing firefighting capability.

3.0 APPROACH

The port wing wall area on SHADWELL, designated as the ISCC test area, was used for these tests (Fig. 1). A post-flashover fire was created in the space called Berthing 2. This fire heated adjacent spaces, in particular the compartments directly above the fire, RICER 2 and CIC. In this test, the fire boundary of interest was formed

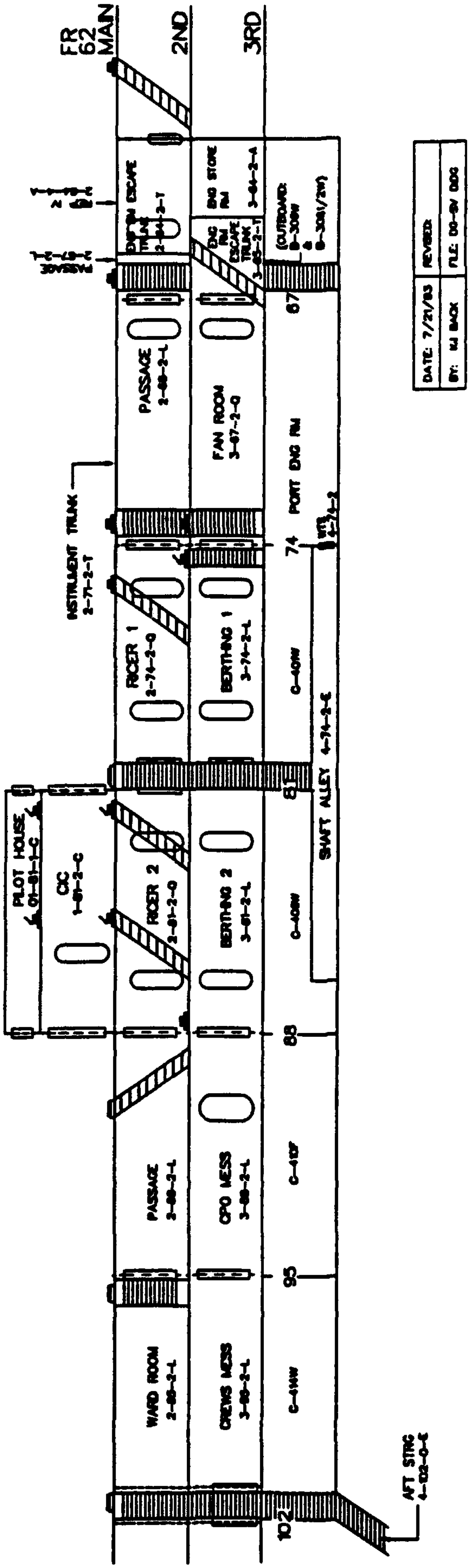

Fig. 1 - ex-SHADWELL, section view, port wing wall ISCC test area

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by the RICER 2 deck. The post-flashover fire in Berthing 2 was allowed to burn uncontrolled for 20 minutes. The fire was then secured and boundary cooling operations commenced. Boundary cooling tactics, procedures, and techniques were investigated by approaching RICER 2 horizontally from RICER 1 or vertically from CIC. Standard Navy equipment, including the variable stream and all purpose handline nozzles, were used by expert firefighters from the SHADWELL ship's force. Alternative equipment, including a garden hose nozzle and water misting attachment to the water motor fan, were evaluated. Key variables, in addition to the equipment and approach, included the level of personnel protection and method of venting steam.

4.0 TEST AREA

Tests were conducted along the port wing wall of ex-USS SHADWELL in the ISCC test area (Figs. 1 and 2). The post-flashover fire was created in Berthing 2 (Fig. 3). Section 7.2 describes the fire threat and temperatures in the fire areas. Figures 4 through 8 show the test areas of interest. Figures 4 and 5 show the second deck RICER spaces. Figures 6 through 8 show the main deck areas. For horizontal boundary cooling of the RICER 2 deck, access was made to RICER 1 via quick acting scuttle (QAS) 1-75-2, which is open to weather on the main deck. Firefighters then gained access to RICER 2 by opening the quick acting watertight door (QAWTD) 2-81-4. For vertical access to RICER 2, firefighters entered CIC via weather through QAWTD 1-81-2. Access to RICER 2 could then be made via QAS 1-81-2 or QAS 1-84-2. Ladders from the CIC scuttles to RICER 2 were removed for these tests. The CIC deck house, constructed of steel, lay on the main deck but was not welded tight to the deck. Gaps between the main deck and the deckhouse structure were sealed with caulk, but the space was neither airtight or watertight at this joint. The space was sufficiently tight to contain steam from the indirect cooling tactics conducted in CIC.

5.0 INSTRUMENTATION

A complete instrumentation plan and description for the ISCC test area is contained in Reference [6]. Figures 3 through 8 show the instrumentation for the areas used in the cooling tests. For analytical evaluation, the following instruments are of interest.

5.1 Thermocouples

Type K, inconel-sheathed thermocouples were used to measure compartment air, deck, and bulkhead temperatures. Bulkhead and deck temperatures were installed under a nut and bolt arrangement as described in Reference [6].

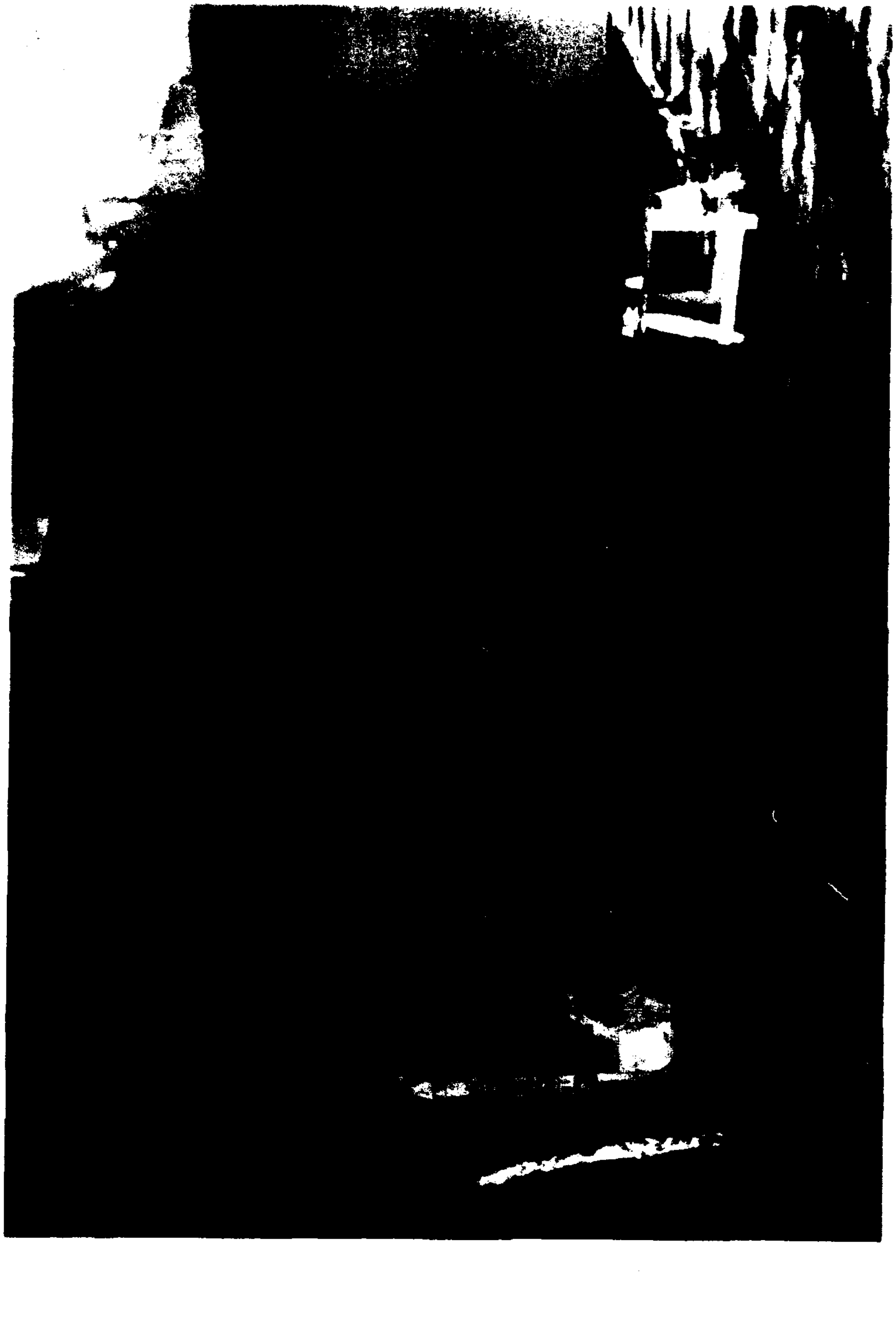

Fig. 2 - Port wing wall ISCC area used for cooling tests

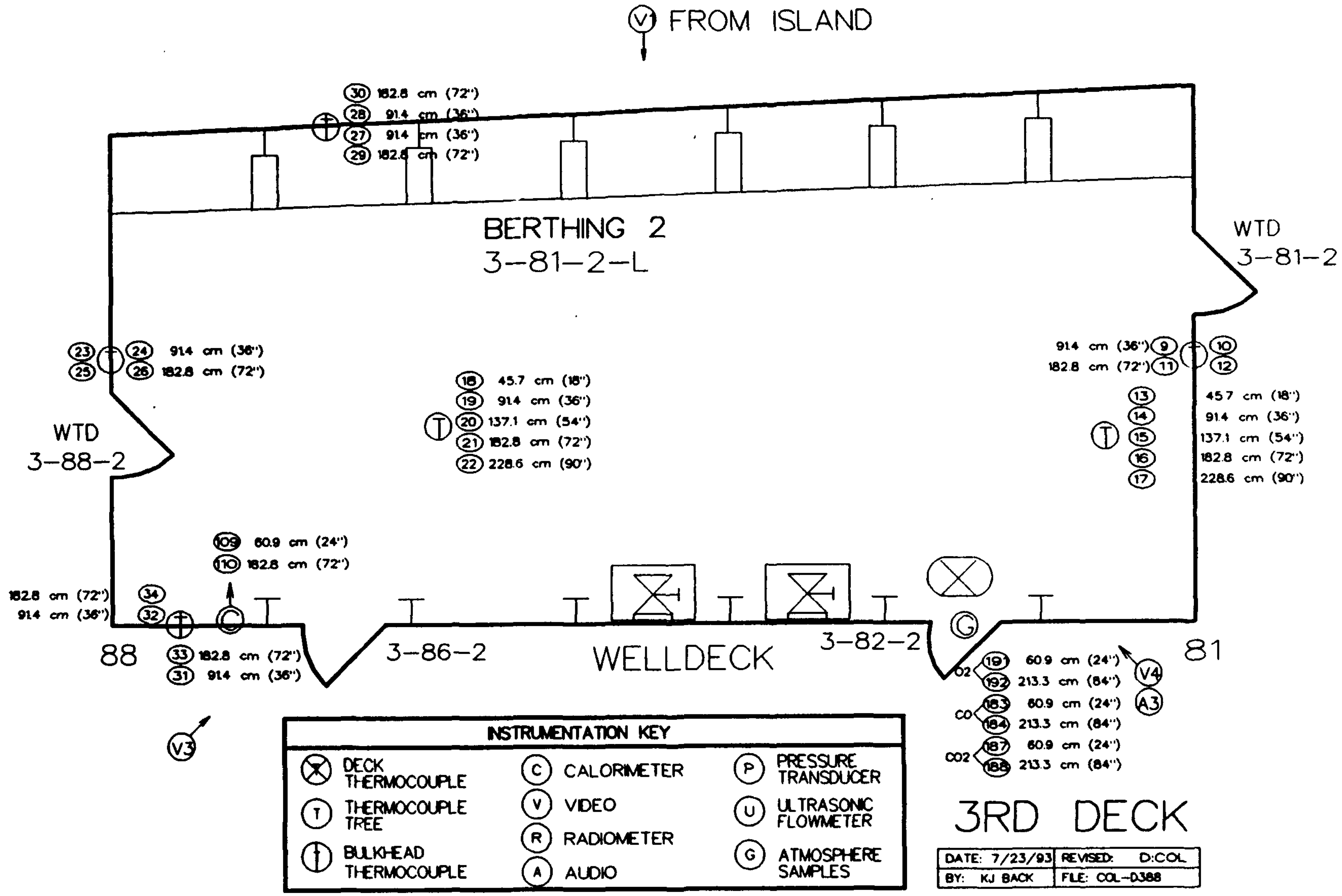

Fig. 3 - Third deck plan view, Berthing 2

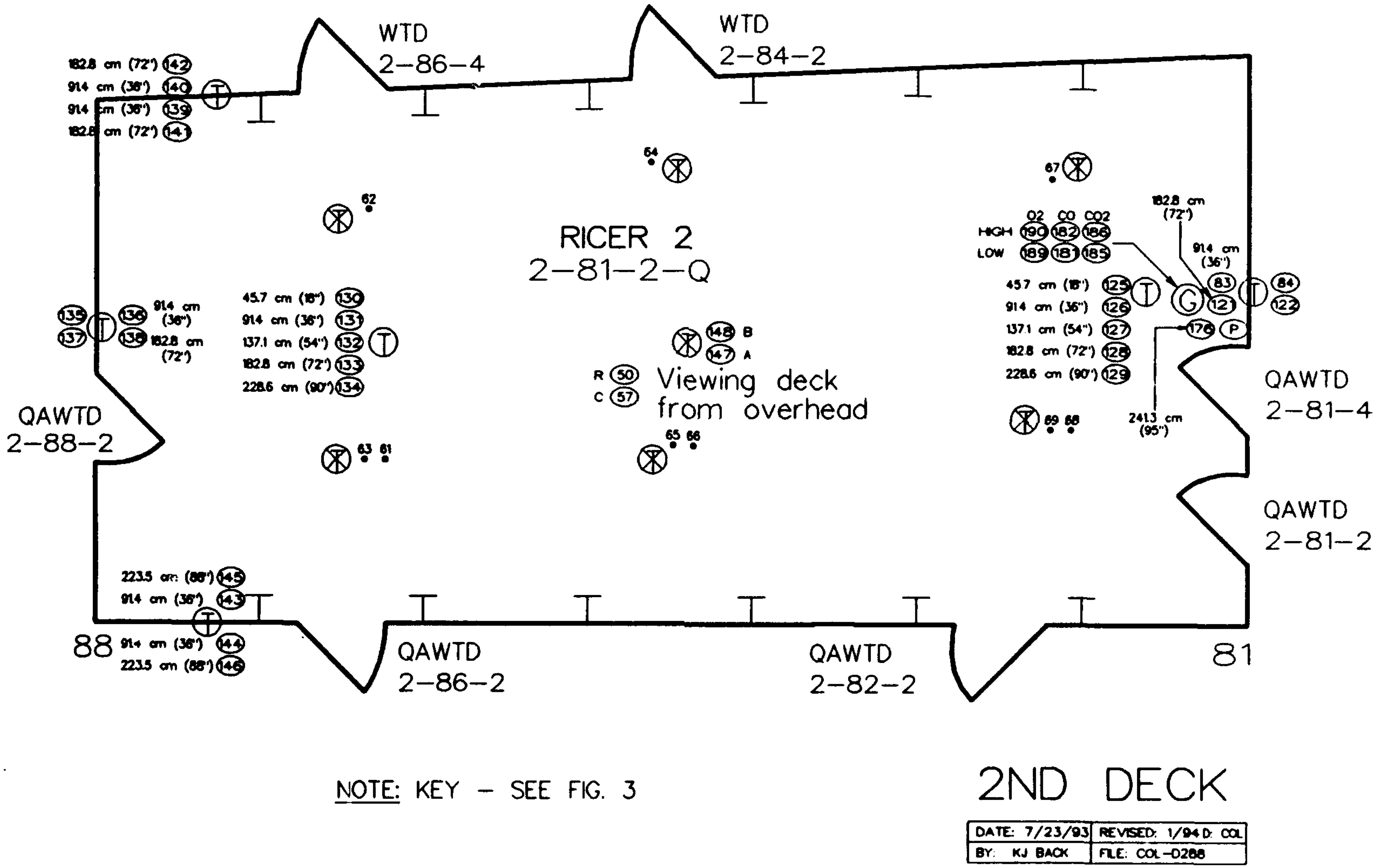

Fig. 4 - Second deck plan view, RICER 2

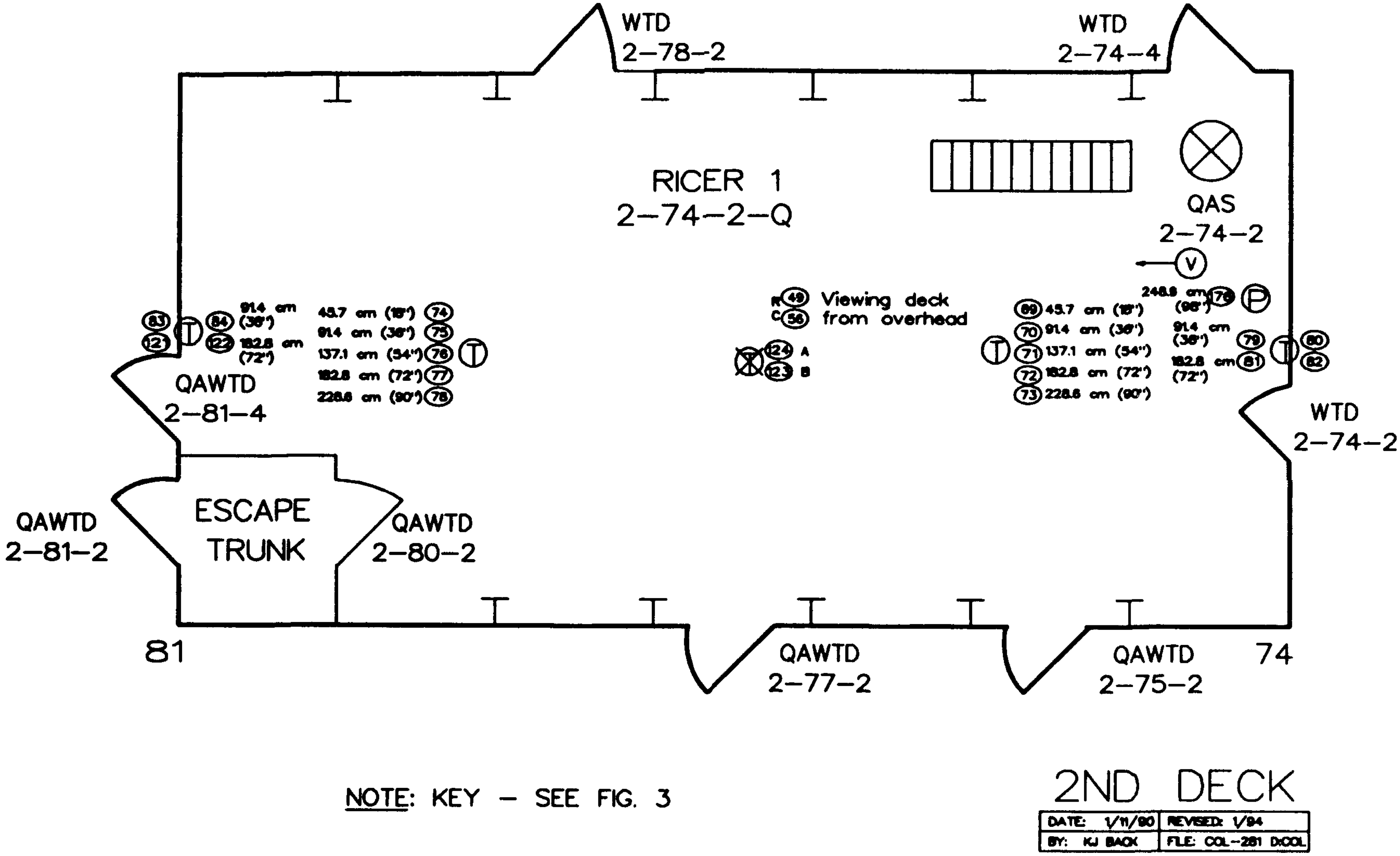

Fig. 5 - Second deck plan view, RICER 1

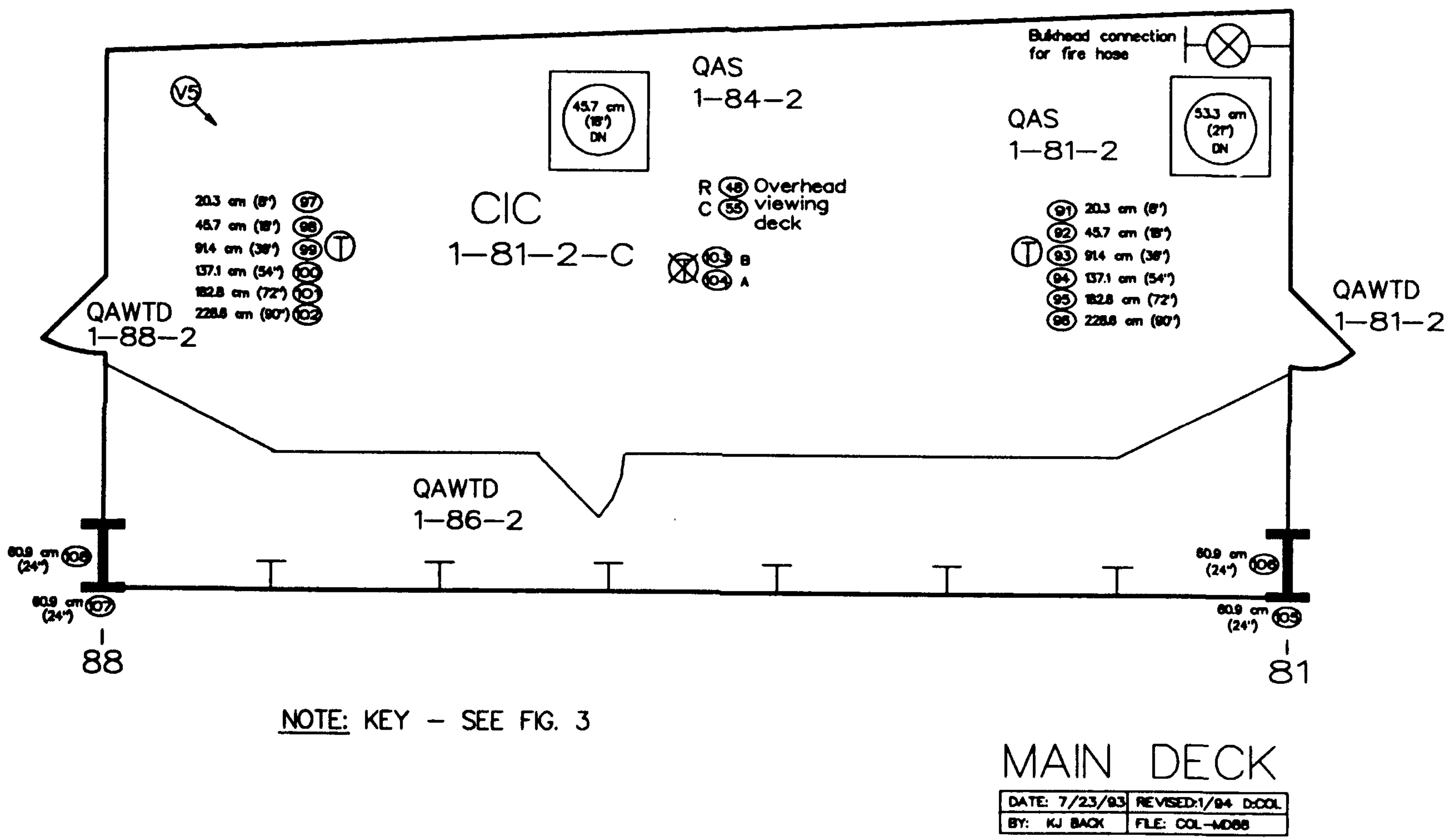

Fig. 6 - Main deck plan view, CIC

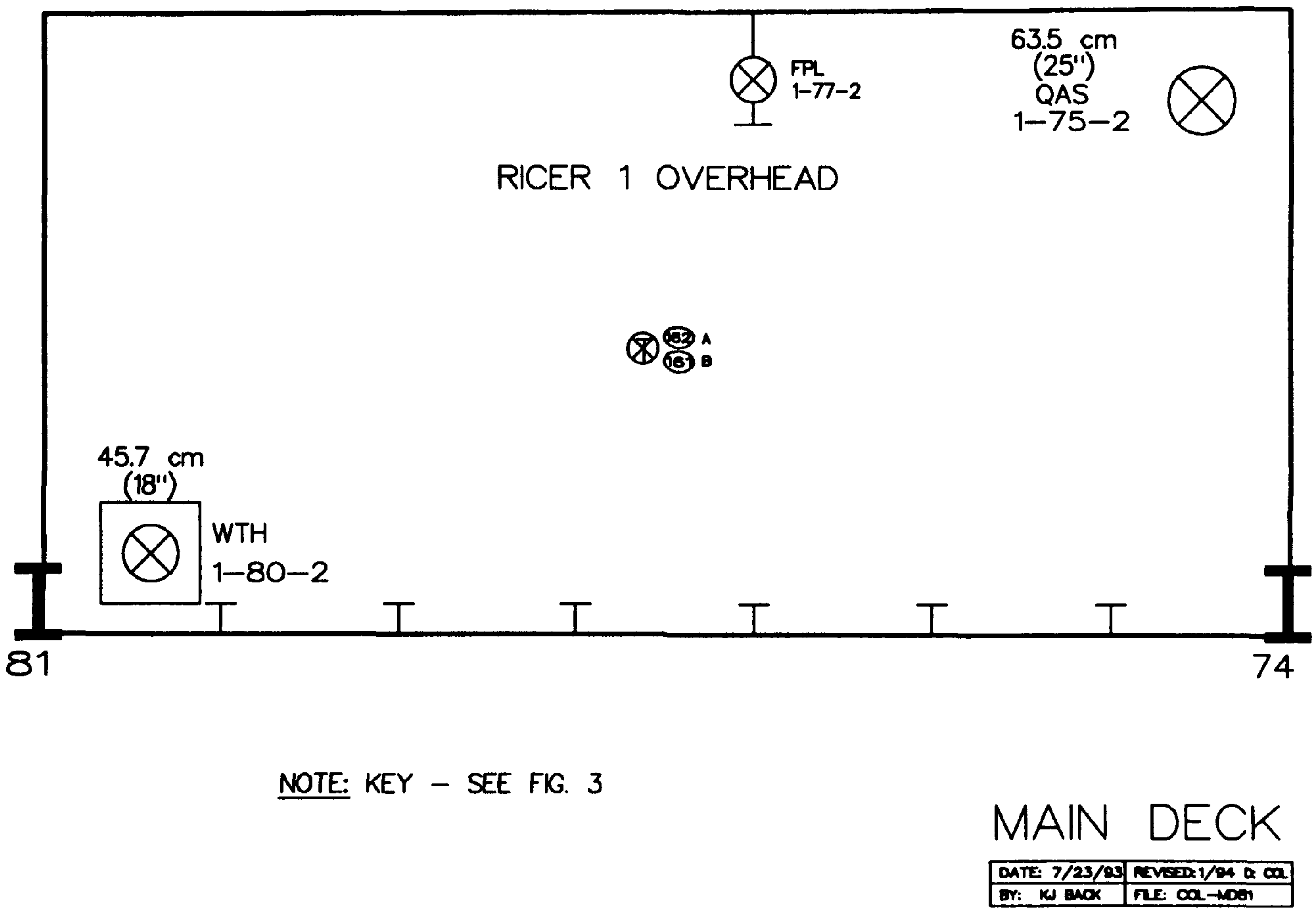

Fig. 7 - Main deck plan view, RICER 1 overhead open to weather

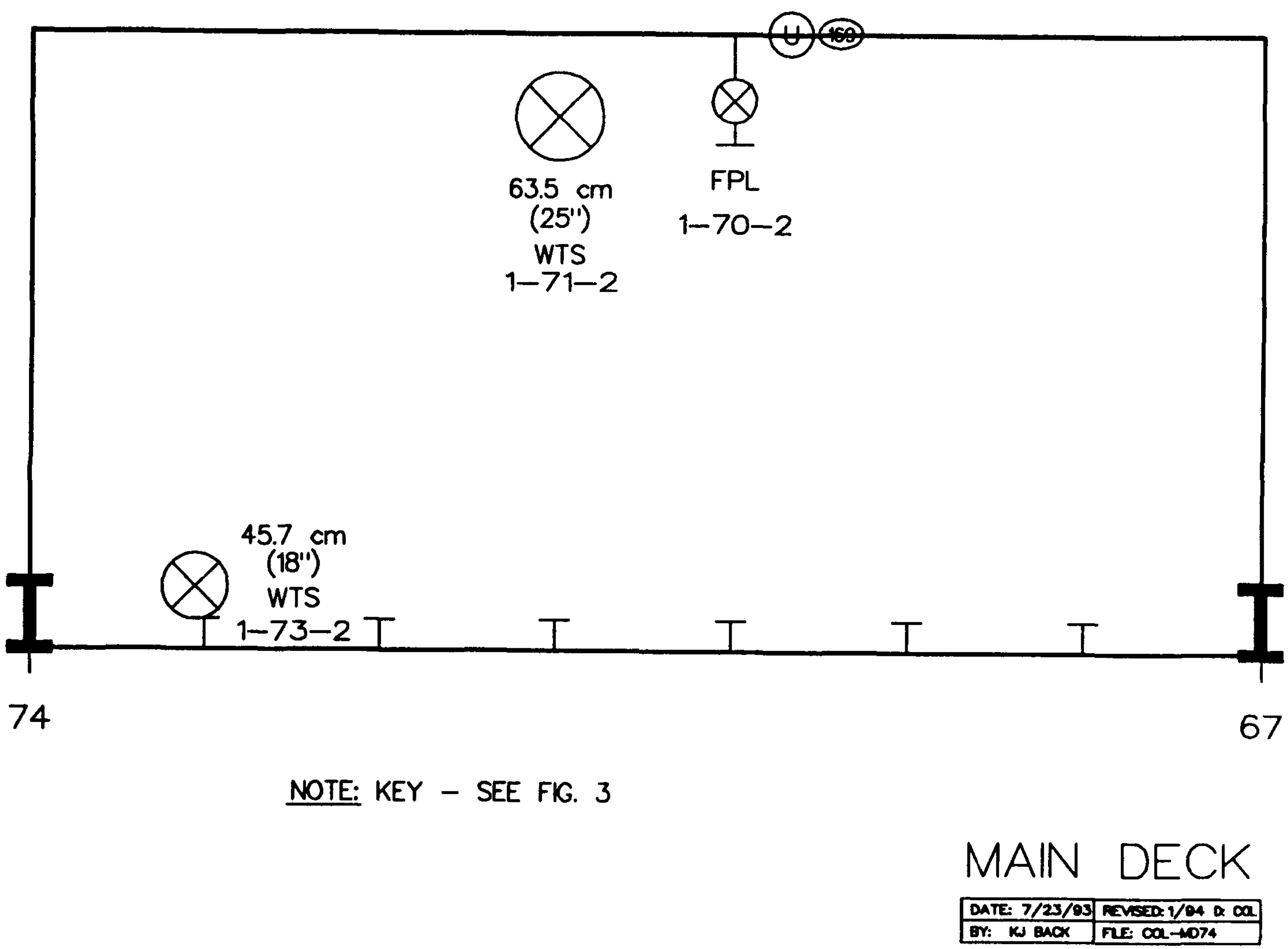

Fig. 8 - Main deck plan view, FR 67-74, open to weather

5.1.1 Air Thermocouples

Vertical strings, five thermocouples per string, were installed on steel chain trees in the following compartments located 46, 91, 137, 183, and 229 cm (18, 36, 54, 72, and 90 in.) above the deck:

(a) Main deck – CIC, along the centerline of the space at FR 83 (Ch. 91-96) and 86 (Ch. 97-102), with an additional thermocouple installed 20 cm (8 in.) off of the deck.

(b) Second deck – in RICER 1 forward and aft; the aft thermocouples (Ch. 74-78) located at FR 79, are used for analysis.

(c) Second deck – in RICER 2, forward at FR 82 (Ch. 125-129) and aft FR 86 (Ch. 130-134).

5.1.2 Deck Thermocouples

(a) Main deck – thermocouples on both sides of the steel deck were located in CIC at FR 84, Ch. 104 on the CIC side and Ch. 103 on the RICER 2 side.

(b) Second deck – thermocouples on both sides of the steel deck were located in RICER 2 at FR 84, Ch. 147 on the RICER 2 side and Ch. 148 on the Berthing 2 side.

(c) Second deck – thermocouples on the RICER 2 side, Channels 61-69, were installed on the RICER 2 deck in conjunction with insulation tests. For the cooling (COL) tests, all of these thermocouples were available for analysis. In the insulation tests where the water motor fan was used, only Channels 62, 64, and 67 were exposed to bare steel. The others were protected by insulation. Reference [7] provides detailed locations for these thermocouples.

5.1.3 Bulkhead Thermocouples

(a) Second deck, RICER 2

  (1) On the FR 81 bulkhead, 91 and 172 cm (36 and 72 in.) above the deck. Channels 81 and 121 were on the RICER 1 side, and Channels 83 and 122 were on the RICER 2 side.

  (2) In RICER 2, on the aft bulkhead, FR 88, Ch. 135, 91 cm (36 in.) and Ch. 137 172 cm (72 in.) above the deck.

5.2 Calorimeters

Gardon-type, water-cooled, wide angle calorimeters were installed to measure total heat flux in the following locations:

(1) In the overhead of CIC, FR 84 (Ch. 55),
(2) In the overhead of RICER 2, FR 84 (Ch. 57), and
(3) In the overhead of RICER 1, FR 77 (Ch. 56).

5.3 Air Pressure Transducers

Air pressure transducers, Sentra Model 1090, were installed in the overhead of RICER 1 (Ch. 176) and RICER 2 (Ch. 175) to measure air pressure in these compartments.

5.4 Water Flowmeters

An ultrasonic water flowmeter (Controlotron 9000) was installed near the fire plug at FR 70 (FPL 1-70-2) to measure water flow to firefighting hoselines and the water motor fan (Ch. 169). This could also measure flow when FPL 1-77-2 was used.

6.0 EQUIPMENT

6.1 Firefighting Equipment

The following standard Navy firefighting equipment was used in the tests:

(1) A Type I, 3.8 cm (1.5 in.) 360 Lpm (95 gpm) vari-nozzle in accordance (IAW) MIL-N-24408 (Elkhart Model SFL, Fig. 9), and

(2) Navy All Purpose Nozzle (APN) with a 1.2 m (4 ft) applicator IAW MIL-N-12314E (Fig. 10).

This equipment was connected to standard MIL SPEC 3.8 cm (1.5 in.) fire hose. In addition, the following experimental equipment was evaluated:

(1) Variable stream, variable flow garden hose-type nozzle (Gilmore "Supreme," Sommerall, PA). This was connected to hard rubber hose, 1.9 cm (0.75 in.) inside diameter with a 0.62 cm (0.25 in.) wall thickness (BF Goodrich GS red, 3/4D, WP 200 psi) (Fig. 11). This was connected to the 3.8 cm (1.5 in.) fire plug by a pipe manifold fabricated by ship's force (Fig. 12). The hose used for these tests is typical of air hose found on Navy ships.

Fig. 9 - Firefighter with full ensemble protection and vari-nozzle

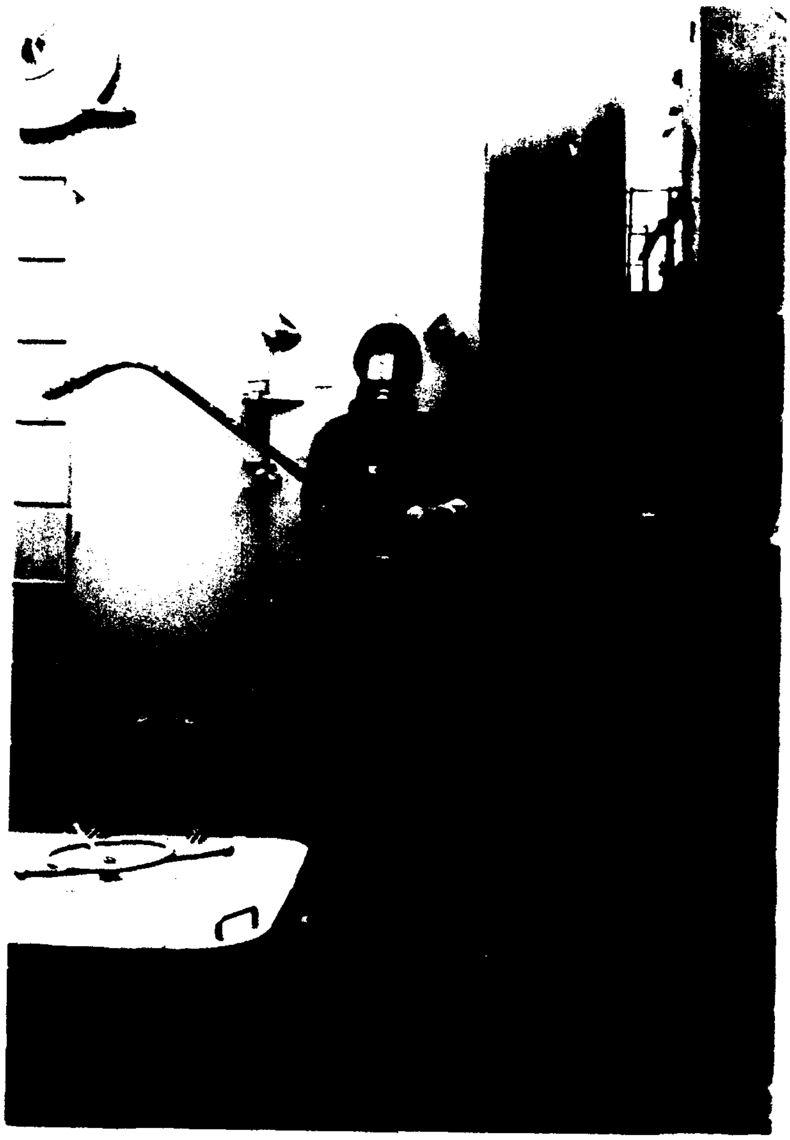

Fig. 10 - Firefighter in intermediate raingear protection and Navy All Purpose Nozzle with 1.2 m (4 ft) applicator

Fig. 11 - Firefighter in minimum coverall protection with 1.9 cm (0.75 in) hose line and nozzle

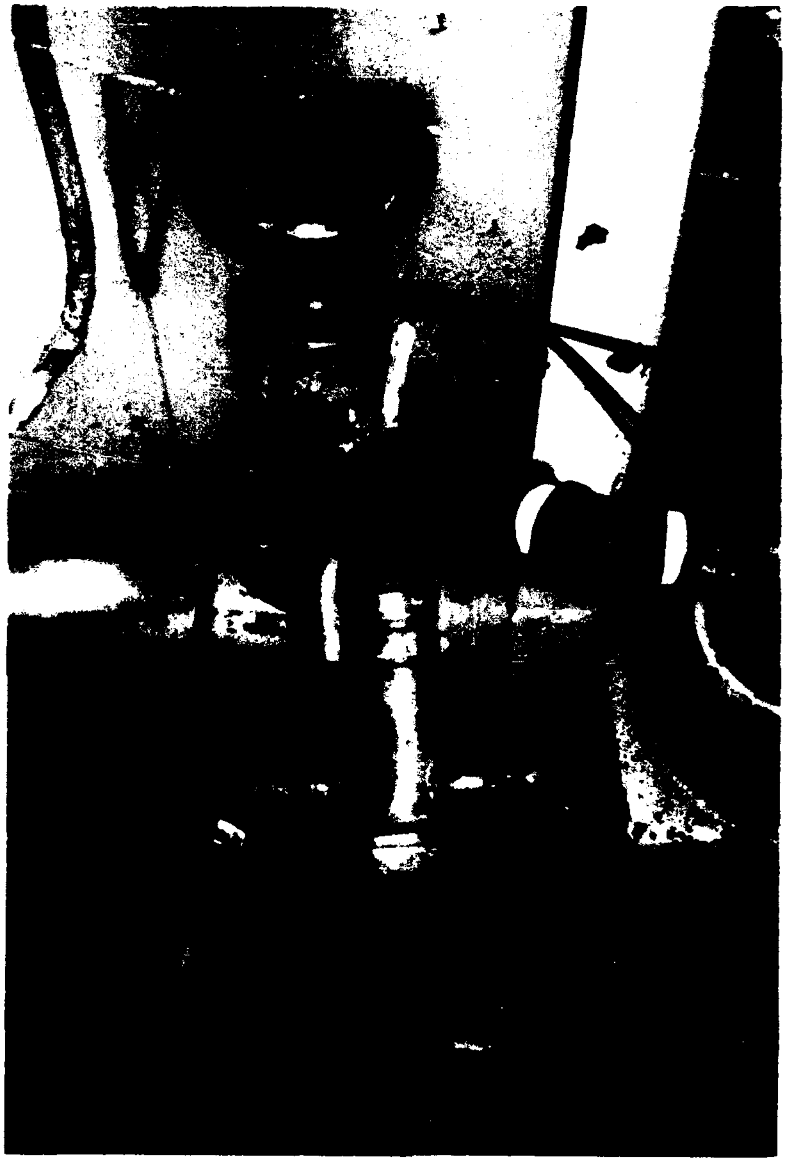

Fig. 12 - Manifold used to connect 1.9 cm (0.75 in) hose to fire plug

(2) Water motor fan (RAMFAN 2000, Model WF-20, manufactured by RAM Centrifugal Products, Inc.) was fitted with a water misting device (Fig. 13). The misting device was a Bete Fog Nozzle Inc. spray nozzle TF10N, with a nominal flow coefficient (k)[1] of 0.65.

6.2 Personnel Protective Equipment

Boundary cooling teams had to be protected to prevent steam burns. Three general levels of personnel protection were used: minimum protection, where coveralls were used to protect bare skin; intermediate protection, where raingear was used to provide an additional layer of protection; and full protection, where the Navy firefighting ensemble (FFE) was used. The specific equipment used included the following:

(1) Minimum coverall protection (Fig. 11)
- (a) Navy engineering coveralls in accordance with (IAW) MIL-C-87093 (NSN 8405-01-204-5409) or common cotton longsleeve work coveralls (MIL-C-87000, NSN 8405-01-057-3494))
- (b) Flashhood IAW MIL-H-24936 (NSN 8415-01-268-3473)
- (c) OBA IAW MIL-B-24692 (NSN 4240-00-616-2875)
- (d) High top leather work boots; sometimes rubber boots were worn
- (e) Battle helmet liner
- (f) Common cotton work gloves (NSN 8415-00-634-5026); sometimes the Navy firefighting gauntlets were used

(2) Intermediate raingear protection (Fig. 10)
- (a) Engineering coveralls
- (b) Wet weather parka (MIL-P-87098, NSN 8405-01-276-4191) and trousers (MIL-T-87099, NSN 8405-01-276-1536)
- (c) OBA
- (d) Flashhood
- (e) Helmet liner; sometimes the Navy firefighter's helmet was used (with and without the protective shield). The raingear parka hood was also used in some tests
- (f) Rubber boots IAW A-A-50371 with trousers tucked into boots
- (g) Heat protective gloves (NSN 8415-01-092-3910) supplied in repair lockers; sometimes the FFE gauntlets were used

(3) Full ensemble protection (Fig. 9)
- (a) Coveralls
- (b) Navy firefighters ensemble IAW MIL-C-24935 (NSN 8415-01-300-6558)
- (c) Navy firefighters helmet (NSN 8415-01-271-8069)
- (d) Flashhood
- (e) OBA

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[1] $k = Q/P^{1/2}$ where Q is flow (gpm) and P is pressure (psi).

Fig. 13 - Water motor fan with mister attachment

(f) Navy firefighters gauntlet-type gloves for use with the firefighters ensemble IAW MIL-G-24934 (NSN 8415-01-296-5767)

(g) Rubber boots IAW A-A-50371 (NSN 8430-00-753-5940)

7.0 SETUP, PROCEDURES, AND FIRE THREAT

7.1 Setup and Procedures

The firefighting equipment described in Section 6.1 was used along the port wing wall of SHADWELL. Three cooling series were conducted: horizontal cooling, where the access to RICER 2 was made horizontally from RICER 1; vertical cooling, where the access to RICER 2 was made vertically from CIC; and water motor fan cooling, where the RAMFAN with mister attachment was used. The RAMFAN was used in both the horizontal and vertical modes.

In the horizontal cooling tests, firefighting equipment was supplied by 30.5 m (100 ft) of 3.8 cm (1.5 in.) hose or 15.2 m (50 ft) of 1.9 cm (0.75 in.) hose connected to FPL 1-70-2. The electric engine fire pump frequency drive was set to 50-55 Hz, which resulted in 1035 Kpa (150 psi) static firemain pressure. A residual pressure of 966 Kpa (140 psi) resulted at FPL 1-70-2 when the 3.8 cm (1.5 in.) hose was being operated. Nominal flow rates of the equipment during boundary cooling were 341-360 Lpm (90-95 gpm) for the vari-nozzle; 250 Lpm (66 gpm) for the APN with applicator; and 38-45 Lpm (10-12 gpm) maximum flow for the garden hose nozzle, with 23-27 Lpm (6-7 gpm) when the device was used to spray a straight stream.

In the vertical cooling tests, equipment was supplied by 15.2 m (50 ft) of 3.8 cm (1.5 in.) fire hose from FPL 1-77-2 to a coupling connection installed in the FR 81 bulkhead of CIC. This supplied either 15.2 m (50 ft) of 3.8 cm (1.5 in.) hose for the vari-nozzle or APN, or 7.6 m (25 ft) of 1.9 cm (0.75 in.) hose for the garden hose nozzle. Flows were essentially the same as in the horizontal tests, with the flow for the garden nozzle slightly greater due to less friction loss.

For the RAMFAN tests, the firemain pressure was set at 966 Kpa (140 psi), which resulted in a residual pressure at FPL 1-70-2 of 938 kPa (136 psi). For the horizontal attack, water was supplied by 15.2 m (50 ft) of 3.8 cm (1.5 in.) hose from FPL 1-70-2 to the fan in RICER 1. The discharge water from the RAMFAN was dumped to a drain in the well deck through 30.5 m (100 ft) of 3.8 cm (1.5 in.) hose from RICER 1, up QAS 1-75-2, and to the well. For the vertical attack, water was supplied by 15.2 m (50 ft) of hose from FPL 1-77-2 to the FR 81 CIC bulkhead connection and then to an additional 15.2 m (50 ft) of hose supplying the RAMFAN. The discharge water was dumped to the well deck by 30.5 m (100 ft) of hose through QAWTD 1-81-2.

The flow of water throughout the RAMFAN water motor was 227 Lpm (60 gpm). With the mister device activated, the total flow was 246-258 Lpm (65-68 gpm). It was estimated that the mister flowed 28 Lpm (7.5 gpm) with the 966 kPa (140 psi) firemain pressure.

Access to RICER 1 for horizontal firefighting was by QAS 1-75-2. This scuttle opening was the only vent from RICER 1 in the horizontal tests. Access to RICER 2 was by QAWTD 2-81-4.

In the vertical evolution, access to CIC was made by QAWTD 1-81-2, which was normally shut to contain steam within CIC. Access to RICER 2 for boundary cooling was by QAS 1-84-2. Access for the RAMFAN tests were by the same routes, with the steam venting routes varied to evaluate different alternatives.

Except for the access to provide indirect cooling, RICER 2 remained tight during the tests. Typically the access opening (QAWTD 2-81-4 or QAS 1-84-2) was cracked open for the time water was applied, then secured. In the early tests, RICER 2 remained essentially airtight. As testing progressed, cracks in the RICER 2 deck and bulkheads allowed some degree of leakage. While attempts were made to seal cracks, the integrity of the RICER 2 deck in the later tests (vertical and RAMFAN) were not equal to that of the earlier tests (horizontal). This affected the potential pressure build-up due to steam in RICER 2.

7.2 Fire Threat

A post-flashover fire was created in Berthing 2 as described in Reference [6]. It consisted of a three-minute burn period of heptane contained in three 1.2 m (4 ft) square pans. This was followed by a continuous 17 minute diesel fuel spray fire, ignited by the fire in the three pans. The flow rate was nominally 5.80 Lpm (1.53 gpm) per pan, 17.4 Lpm (4.6 gpm) total. Air was supplied naturally to the fire area by vent openings in the hull structure and the open doors to the well deck. The estimated heat release rate of this fire, based on complete combustion, is approximately 9.2 MW.

The total burn time was 20 minutes, during which all other compartments in the test area were sealed. At the end of 20 minutes, the fueling system piping was blown down to remove residual fuel, and the fueling system secured. The firefighting team was then called away. Typically, the team responded and was at the boundary within two to four minutes from the end of the preburn.

Average Berthing 2 fire compartment temperatures, taken from the Insulation Test Series at thermocouple channels 20, 21, and 22 are shown in Fig. 14. These overhead temperatures were on the order of 1000°C. References [6] and [7] provide detailed analysis of the design fire, Berthing 2 temperatures, and the effects of wind.

Appendix A provides representative data for these tests, including RICER 2 air temperatures. The data show that, at the end of the background burn period, temperatures in RICER 2 were on the order of 270 - 335°C. RICER 2 started to naturally cool so that when firefighters started to cool the space, temperatures in RICER 2 had dropped by a maximum of 30°C.

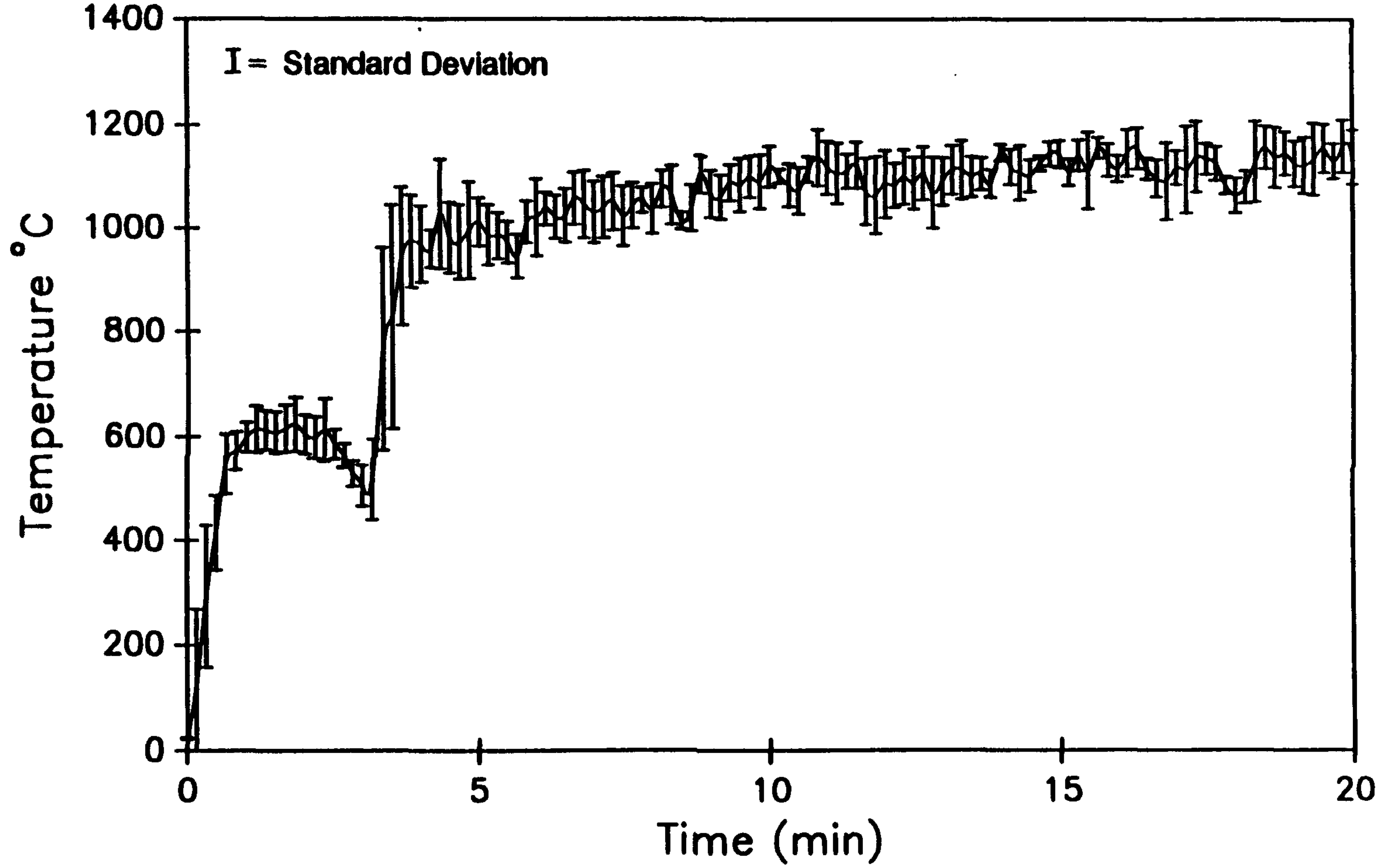

Fig. 14 - Berthing 2 upper layer temperature (average of TC's 20, 21 & 22)

8.0 RESULTS

Three series with a total of 23 boundary and compartment cooling tests were conducted. In the first series, COL_1 through COL_9, horizontal access to RICER 2 was investigated. Vertical access was investigated in COL_10 through COL_16. The water motor fan was investigated in INS_4 through INS_10. These tests were conducted in conjunction with insulation tests as reported in Reference [7].

Appendix A provides detailed data to assess cooling efficiency for each test, including RICER 2 air, bulkhead, and deck temperatures. For tests with the horizontal access scenario, data for RICER 1 air temperatures and total heat flux at the overhead are provided. This can be used to assess the impact of heat stress on the firefighters. Likewise, air temperatures and total heat flux for CIC are provided for the vertical access scenarios.

8.1 Horizontal Access Cooling

Table 1 summarizes the results of the horizontal cooling tests. The bulkhead at FR 81 was cooled at approximately 10 minutes after ignition while the fire in Berthing 2 was still burning. After the Berthing 2 fire was secured at 20 minutes, firefighters were permitted to cool RICER 2.

8.1.1 RICER 2 Cooling

In COL_1, the FR 81 bulkhead was cooled shortly after ten minutes after ignition. This was a scoping test to determine if the 1.9 cm (0.75 in.) hoseline would be adequate. The intent was to acclimate the firefighters to the heated conditions. The FR 81 door was cracked, and water sprayed in the space 4-5 times. The data (Figs. A1 - A9) indicate only modest cooling in RICER 2 and very little cooling of the deck. Cooling was improved in COL_2 (Figs. A10 - A18) and COL_3 (Figs. A19 - A27), where the short water burst tactic (e.g., 76-114 Lpm, 20-30 gpm) was more aggressively used. Personnel indicated that the best cooling was in Test COL_3, where the most water was used. Deck temperatures in COL_2 were lower, probably due to the use of the straight stream with the vari-nozzle.

Tests COL_4 through COL_6 (Figs. A28 - A54) were a repeat of COL_1 through COL_3, except that the firefighting personnel wore full protection using the Navy firefighting ensemble. In COL_4, the 1.9 cm (0.75 in.) hose was used. More water and a more aggressive approach was used compared to COL_1. This is reflected in better cooling of RICER 2 air and deck temperatures compared to COL_1. In COL_5, the FR 81 boundary was cooled at about 11 minutes into the test. After the fuel was secured, cooling of RICER 2 was initiated. There was significant heat in RICER 1 as a result of cooling the bulkhead at FR 81 and aggressively cooling RICER 2 (Figs. A43 - A44). The steam produced by cooling the FR 81 bulkhead heated RICER 1. RICER 1 was also heated by steam flowing from RICER 2 through QAWTD 2-81-4 during the RICER 2 cooling evolutions. In COL_6, where the APN with applicator was used, the bulkhead was aggressively cooled (394 L, 104 gal) before the cooling of RICER 2 was initiated. As

Table 1. Boundary Cooling of RICER 2 using Horizontal Access

Test	Equipment	Dress[1]	Tactic[2]	Firefighter Stay Time (min.)	Total Water Used (L (gal))	Procedural Comments	Results/Comments
COL_1	1.9 cm (0.75 in.) hoseline	CV	Int.	~20	180.4 (47.6)	Enter at 10 min. to cool BH FR 81; attack R2 after 20 min. burn time	BH FR 81 cooled even though it may not really be needed; rubber shoes/boots with insulation would probably protect better
COL_2	Vari-nozzle	CV	Int.	25	493 (130)	Same scenario as COL_1, with vari-nozzle	Hard hat/helmet required to protect head from dripping hot water in R1 (condensed from R2 steam)
COL_3	APN with 1.2 m (4 ft) applicator	CV	Int.	23	762 (201)	Same scenario as COL_1, with APN	"Best cooling yet in R2;" vari-nozzle easier to operate than applicator for this scenario
COL_4	1.9 cm (0.75 in.) hoseline	EN	Int./ Cont.	21.5	313 (82.6)	Repeat COL_1 - COL_3 scenario with firefighter ensemble and more aggressive attack	Needed to cool hands every 30 s after pain threshold was reached; need a handle device to operate the door, which swings in (UK suggests lanyard)
COL_5	Vari-nozzle	EN	Int.	22	493 (130)	Repeat COL_4 with vari-nozzle	Estimated 80% tolerance level

NOTES: 1 EN - Ensemble; RG - Raingear; CV - Coveralls
2 Cont. - Continuous water application; Int. - Intermittent water application

Table 1. Boundary Cooling of RICER 2 using Horizontal Access (Continued)

Test	Equipment	Dress[1]	Tactic[2]	Firefighter Stay Time (min.)	Total Water Used (L (gal))	Procedural Comments	Results/Comments
COL_6	APN with 1.2 m (4 ft) applicator	EN	Int.	23	394 (104) cooling boundary; 2047 (540) total	Repeat COL_4 with APN	Significant heat flux in R1 in this test
COL_7	Vari-nozzle	RG	Int.	21	341 (90) BH cooling	Repeat COL_5 with raingear	Steam burns to hands, feet, and legs; raingear did not cover boots
COL_8	APN with 1.2 m (4 ft) applicator	RG	Int.	21	432 (114) BH cooling; 1790 (473) total	Repeat COL_6 with raingear; firefighter cooled briefly by 0.75 in. back-up line	"Rain" in R1, approx. 2-3 in. of water on R2 deck in the low spots, not a complete water layer; flame safety lamp installed in R1 at FR 81 went out after initiating second attack on R2
COL_9	1.9 cm (0.75 in.) hoseline	RG	Int./ Cont.	22	95 (25) BH cooling; 431 (114) total	Repeat COL_4 with raingear	Very hot to firefighters, high flux in R1; water laying in R2 deck "dimples;" less visible steam in this test, better visibility

NOTES:
1 EN - Ensemble; RG - Raingear; CV - Coveralls
2 Cont. - Continuous water application; Int. - Intermittent water application

expected, the bulkhead and RICER 2 temperatures were reduced significantly (Figs. A46 - A50), but at a penalty of increased heat stress to the firefighters (Figs. A52 and A53). Significant rises in the RICER 1 temperature and heat flux were not observed until cooling of RICER 2 was initiated. When RICER 2 was vented at the end of the test, there was a sharp increase in temperature and heat flux in RICER 1 (e.g., Figs. A25 and A26 at 32 minutes).

Tests COL_7 through COL_9 (Figs. A55 - A81) were a repeat of the two previous test series, except that firefighters wore intermediate, raingear protection. Aggressive tactics were used in COL_7 and COL_8, where the vari-nozzle and APN with applicator were used. In both situations, the boundary at FR 81 was cooled and then RICER 2 cooled aggressively using the short water burst tactic. The cooling results were similar to those in COL_5 and COL_6. In COL_9, the small diameter hoseline was used in a similar manner to cool the bulkhead and then cool RICER 2. Heat stress to the firefighters was similar to the heat in COL_7 and COL_8, even though less water was used (Figs. A62, A71, and A80).

An attempt was made in the COL_4 through COL_9 tests to apply a layer of water to the RICER 2 deck for cooling. As the tests progressed, the deck started to warp and create pockets where water could lay. In some cases, this created additional heat, particularly in COL_9. The puddled water created additional steam which contributed to increased heat stress to the boundary cooling personnel.

8.1.2 Clothing and Heat Stress

Table 2 shows that the maximum heat flux occurred when the most aggressive tactics were used, COL_4 - COL_9. For comparative purposes, a heat flux of 21.5 kW/m^2 (1.9 Btu/ft^2-s) directly to bare skin results in pain after 2.3 seconds and skin blistering after 3.4 seconds [8]. A heat flux of 2.5-5 kW/m^2 (0.22 - 0.44 Btu/ft^2-s) is the pain threshold for bare skin [9]. Additional heat flux data as it affects personnel are summarized in Reference [10].

Stay time, i.e., the time firefighters stayed in the RICER 1 area, was essentially equivalent for all tests, 20-23 minutes. When coverall protective gear was used, the firefighters were less aggressive as indicated by the water usage in COL_1 - COL_3. For coverall protection, firefighters indicated that rubber-soled shoes are probably required to protect feet from burns. Some type of hard helmet, e.g., a battle helmet liner, was required in addition to the flashhood to protect against "rain" in RICER 1. This rain was actually hot water condensing from steam in the RICER 1 area.

With the full Navy firefighters ensemble, the cooling team could be more aggressive as indicated by the water usage. The use of more water, particularly in laying a layer of cooling water in RICER 2, resulted in significant heat insult to the cooling team. In COL_4, where the 1.9 cm (0.75 in.) hoseline was used, the nozzleman had to cool his hands every 30 seconds after his pain threshold was reached. In COL_5, where the attack team stayed on location 22 minutes and used 493 L (130 gal) of water, the team leader qualitatively estimated that he was at the 80% tolerance level. This was an

educated guess based on past experience on his ability to perform. The 80% level indicates that he was near his maximum stay time.

Table 2. Maximum Heat Flux in RICER 1 Overhead During Horizontal Access

Test	Maximum Flux (kW/m^2 (Btu/ft^2-sec))	
COL_1	7	0.62
COL_2	18	1.59
COL_3	8	0.71
COL_4	14	1.23
COL_5	20	1.76
COL_6	22	1.94
COL_7	16	1.41
COL_8	24	2.12
COL_9	23	2.03

The neck area was particularly vulnerable to steam insult. After several encounters with steam blasts, firefighters were careful to seal their neck area with the flashhood, helmet ear bobs, and ensemble collar as shown in Figure 15.

When raingear was used in COL_7, the cooling team sustained steam burns to their hands, feet, and legs. Since the raingear did not cover their boots, there was a "weak link" at the boot/trouser interface. Personnel started to tuck their leggings around the rubber firefighting boot as shown in Fig. 16. This reduced the steam insult at this "weak link."

Generally, an increase in the level of protection allowed more aggressive boundary cooling tactics, but at a penalty of increased heat stress due to heat and steam.

8.1.3 <u>Boundary Cooling Tactics and Equipment</u>

A general issue during the boundary cooling tests was the need to cool the boundaries. In particular, there was a question of whether to cool FR 81. Temperatures of FR 81 when boundary cooling was initiated approximately 10 minutes into the test were in the 40°C range. This temperature is below the ignition temperature of most Class A materials, including cable insulation. Because the temperatures were relatively low, steam build-up was moderate. However, cooling of the boundary did contribute to overall heat stress and stay time. Unless Class A material is in imminent danger of igniting, there may be no need to cool the boundary since the net result is an increase in

Fig. 15 - Neck area protected by flashhood, ear bobs and collar

Fig. 16 - Rain gear trouser tucked around rubber boot to protect against steam burns

heat stress. Data from the fire dynamics report indicate that ignition temperatures at the FR 81 bulkhead at the second deck will not be achieved during the 20-minute threat studied here [6]. Deck temperatures in RICER 2 are clearly in the ignition range; intervention would be recommended for this boundary.

It was found that the vari-nozzle was easier to handle in the horizontal access scenario than the APN with applicator. The nozzles provided essentially equivalent cooling to the space. The vari-nozzle was probably more effective for deck cooling since the straight stream could be used. The APN with applicator was probably more efficient for overall compartment (air) cooling due to the finer pattern of water.

Because of its inward swing to RICER 2, QAWTD 2-81-4 was difficult to secure between each indirect cooling attack. The access team fabricated their own metal bar with a hook. This allowed them to close the door without standing or kneeling directly in front of the opening. This reduced the steam insult from RICER 2, i.e., they were not directly in the steam path. The UK Ministry of Defence recommends the use of a lanyard [11].

8.2 Vertical Access Cooling

Table 3 summaries the results of the vertical cooling tests, COL_10 - COL_16. The CIC deck was cooled briefly by personnel after the 20-minute post-flashover fire in Berthing 2 had been secured. The boundary cooling team then accessed RICER 2 via an opening in the QAS 1-84-2. Although the deckhouse was not welded to the deck, the space was relatively tight, with no dedicated venting to weather. Again, the short water burst tactic was generally used to cool the CIC deck. Table 4 shows the maximum heat flux at the overhead of CIC for each test. This heat flux is measured at the overhead of CIC using a wide angle calorimeter viewing down toward the deck from the overhead.

8.2.1 RICER 2 Cooling

In COL_10, firefighters wearing ensembles used an APN with 1.2 m (4 ft) applicator to cool RICER 2. A metal hatch cover was fabricated to fit over the scuttle opening at QAS 1-84-2. This cover had a 15.2 cm (6 in.) opening which was covered by a removable piece of metal. A 6.4 cm (2.5 in.) pipe nipple through which the applicator could be inserted was welded to the removable piece (Fig. 17). The idea was to seal the access opening as tight as possible to reduce heat stress to the boundary team. In COL_10, the pipe nipple hole was too small to allow the applicator to be worked, i.e., rotated around the compartment. The hole was just big enough for the applicator tip (spud). Visibility in CIC was poor due to the initial boundary cooling. Even though the

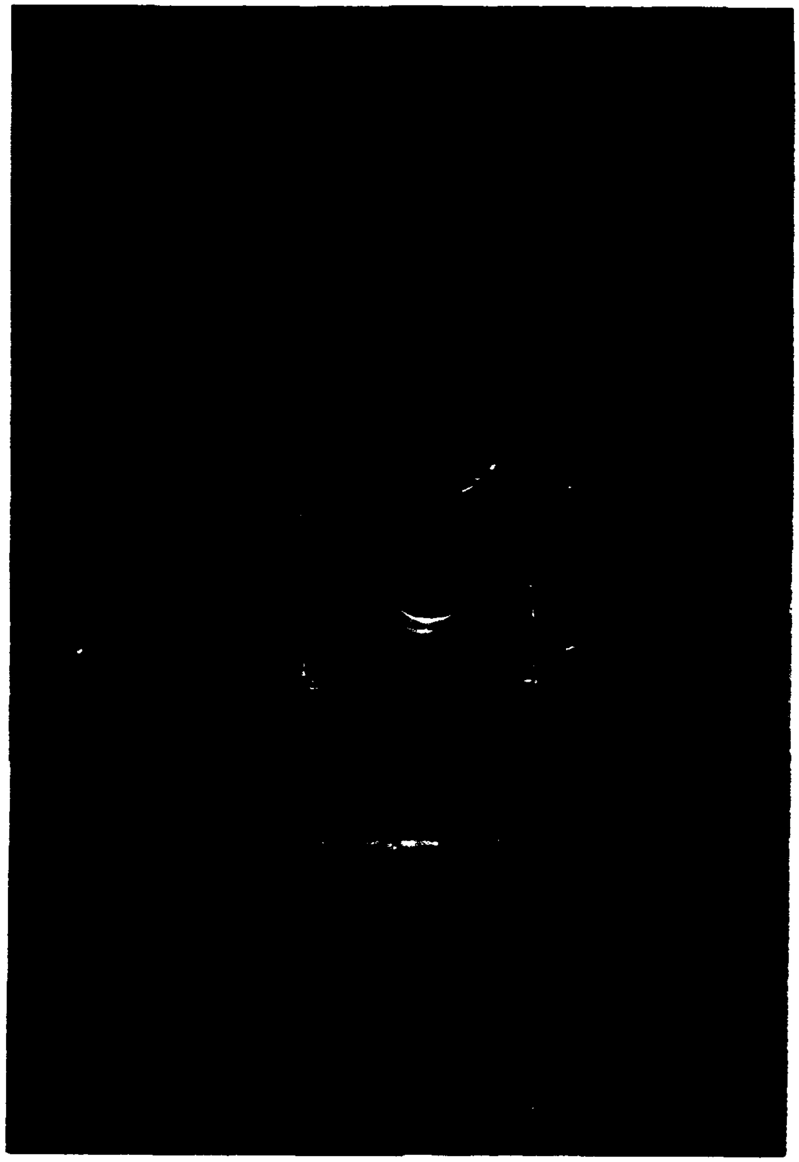

Fig. 17 - Hatch cover used for indirect cooling in vertical access evolutions

Table 3. Boundary Cooling of RICER 2 Using Vertical Access

Test	Equipment	Dress[1]	Tactic[2]	Firefighter Stay Time (min.)	Total Water Used (L (gal))	Procedural Comments	Results/Comments
COL_10	APN with 1.2 m (4 ft) applicator	EN	Cont.	14	53 (14) to cool deck 1652 (436) total	Scenario - below decks vertical cooling with no relief vent	Visibility poor in CIC; APN spud hole was too small, could not maneuver nozzle; stay time reduced compared to other tests, but still had some energy left when they exited
COL_11	APN with 1.2 m (4 ft) applicator	CV	Cont.	Initial stay time short (1.5 min.); cooled off and reentered for an additional 7.6 min.; 9.2 min. total	152 (40) to cool CIC deck 1595 (405) total	Repeat COL_10 with coveralls; pressure spike of 0.5 psi in RICER 2	Firefighters had to exit CIC almost immediately when R2 cooling initiated; reentered and cooled R2 with CIC QAWTD 1-81-2 open to vent CIC
COL_12	APN with 1.2 m (4 ft) applicator	EN	Cont./ Int.	4 + 6 = 10 min. total	140 (37) to cool CIC deck 1607 (424) total	Repeat COL_10 with size of access hole increased; firefighters had to back out, reentered	"Tornado" sound in R2; firefighters "steamed out" due to garment weak points (OBA/neck, wrists); location of APN spud important in cooling efficiency
COL_13	1.9 cm (0.75 in.) hoseline	EN	Cont.	7	38 (10) to cool CIC deck 227 (60) total		Spray cooled only a small area of the deck; steam insult to wrists, feet; estimated 95% tolerance; COL_10 - COL_13 indicate that continuous attack vertically from an unvented compartment is not an effective technique – too much steam

NOTES:
1 EN - Ensemble; RG - Raingear; CV - Coveralls
2 Cont. - Continuous water application; Int. - Intermittent water application

Table 3. Boundary Cooling of RICER 2 using Vertical Access (Continued)

Test	Equipment	Dress[1]	Tactic[2]	Firefighter Stay Time (min.)	Total Water Used (L (gal))	Procedural Comments	Results/Comments
COL_14	APN with 1.2 m (4 ft) applicator	EN	Int.	12	1656 (437)	Hose lowered down scuttle; changed tactic from continuous flow to intermittent flow	Scuttle height affects water efficiency
COL_15	Vari-nozzle	EN	Int.	8	190 (50) to cool CIC deck 1402 (370) total	Entire scuttle area used for access to drop nozzle into R2	Nozzle dropped down scuttle 3-4 ft, pattern varied; pressure build-up in CIC; cooled hands during the test, also cooled CIC intermittently
COL_16	Vari-nozzle	RG	Int.	8	140 (37) to cool CIC deck 1482 (391) total BH cooling	Repeat COL_15 with RG; entire scuttle area used for access	Vari-nozzle best for cooling, but APN also good; better sense of steam condition with raingear; 80% tolerance

NOTES:
1 EN - Ensemble; RG - Raingear; CV - Coveralls
2 Cont. - Continuous water application; Int. - Intermittent water application

Table 4. Maximum Heat Flux in CIC Overhead During Vertical Access

Test	Maximum Flux (kW/m^2 (Btu/ft^2-sec))	
COL_10	34	3.0
COL_11	28	2.5
COL_12	25	2.2
COL_13	17	1.5
COL_14	14	1.3
COL_15	24	2.1
COL_16	28	2.5

applicator tip could not be "worked," cooling of RICER 2 air and deck was generally good, compared to the effectiveness of the horizontal cooling tactic (Figs. A82 - A90). COL_11 (Figs. A91 - A99) was a repeat of COL_10, except that the boundary team wore coveralls. On their initial attack on RICER 2, the team was immediately driven out by steam. They cooled off and reentered the space, but had to leave QAWTD 1-81-2 open to vent CIC during the remaining cooling evolution. Cooling of RICER 2 was a function of the time of water application (Fig. A91, A92, and A99).

COL_12 (Figs. A100 - A108) was a repeat of COL_10 except that both continuous and intermittent (short burst) water application tactics were used. The 6.4 cm (2.5 in.) coupling was abandoned in favor of using the entire 15.2 cm (6 in.) diameter hole in the scuttle access plate. A smoke blanket (wool berthing blanket) was placed over the access hole during the indirect attack. When water was applied continuously, the cooling team heard a "tornado roar" from the steam build-up. Steam drove them from the space after four minutes; after cooling off, they returned for another six minutes. Cooling of RICER 2 was a function of the location of the nozzle and its distribution pattern. Some areas were cooling immediately and rapidly; others were not (Figs. A102 - A105). The results of the steam on the smoke blanket are shown in Fig. 18.

COL_13 (Figs. A109 - A117) was a repeat of COL_12, with the 1.9 cm (0.75 in.) hose line used continuously to cool RICER 2. Only a small area of the CIC deck was cooled to reduce the initial steam insult. Because of the small pattern of garden nozzle and the inability to extend the nozzle down into the compartment, only portions of RICER 2 were cooled (Figs. A109 - A114). Substantial steam was still created by this low flow nozzle.

Fig. 18 - Smoke blanket after COL_12 indirect vertical cooling test

COL_14 through COL_16 were used to investigate intermittent water spray tactics. In COL_14, personnel wearing the ensemble used the APN applicator (Figs. A118 - A126). The short burst/intermittent attack was effective in COL_14 with the APN and COL_15 (Figs. A127 - A135) and COL_16 (Figs. A136 - A144) with the vari-nozzle. The overall steam insult to personnel was less in these tests compared to the continuous attack techniques. Table 4 shows maximum flux levels on the order of 14-28 kW/m^2 (1.3 - 2.5 Btu/ft^2-s) for tests involving the intermittent technique (COL_14 - COL_16). While peak levels were approximately the same as for the continuous attack, the duration of high flux levels for the intermittent attack (e.g., Fig. A143) were less than those for the continuous attack (e.g., Fig. A98). Qualitatively, the vari-nozzle was judged to be best for cooling RICER 2 compared to the APN with applicator which was also judged to be good. It is difficult to draw any quantitative conclusion based on the data (Figs. A118, A119, A127, A128, A136, and A137) since cooling was strongly influenced by the intermittent technique.

8.2.2 Clothing and Heat Stress

In COL_11, it was determined that boundary cooling personnel could not mount an aggressive (continuous water application) cooling attack with only coverall protection without venting CIC. The remainder of the tests were performed with greater protection, particularly the full ensemble. Intermediate protection without venting (COL_16) is probably a borderline situation. Even with the ensemble, the maximum stay time was ten minutes. The higher stay time in COL_10 (14 minutes) is attributed to the inefficiency of the indirect tactic. Overall, stay times in the vertical access tests ranged from 7-14 minutes, one-third to one-half the stay times observed in the horizontal scenarios. Heat flux was observed to be less when the intermittent cooling method was used. Even with this tactic, venting of CIC is recommended when a vertical attack is used.

Weak points in the firefighters ensemble were identified in these tests. They include the gloves (wrists and hands), neck, OBA face piece area, ankles, and feet.

8.2.3 Boundary Cooling Tactics and Equipment

The 1.9 cm (0.75 in.) hoseline was not particularly effective for the vertical access scenario. The low flow rate and relatively small pattern limited its use. This limitation was also exaggerated by the small access hole and height of the raised scuttle at FR 84. Personnel had to reach down into the opening with their hands to control the nozzle. This exposed their wrists and arms to steam burns.

The configuration of the raised scuttle (Fig. 19) also affected the use of the APN and vari-nozzle. If the nozzle is not located down far enough below the raised deck area and any overhead stringers, the pattern will be obstructed. This was observed in COL_12 and corrected in COL_13 where the APN applicator spud was located below the structural ribs in the overhead. This resulted in overall greater cooling effectiveness as indicated by the rapid flash to steam of water. This is also a factor for the vari-nozzle, which had to be lowered 0.9 - 1.2 m (3-4 ft) in COL_15 to be effective.

Fig. 19 - Raised scuttle in CIC

While the access hole to fit the nozzle "spud" of the APN applicator can be as small as 6.3 cm (2.5 in.), a larger hole (on the order of 15.2 cm (6 in.) is required to be able to "work" the nozzle for more efficient cooling. The vari-nozzle with the pistol-grip handle requires a larger hole, on the order of 45.7 cm (18 in.) for indirect access. A smoke blanket can be used to seal any openings around the hole.

8.3 Water Motor Fan Cooling

Investigation of the cooling of RICER 2 using the water motor fan with mister was conducted in tests INS_4 - INS_10. Table 5 summarizes the results. Data are presented in Appendix A, Figs. A143 - A213. A vertical cooling procedure was used for INS_5a and 6. Horizontal cooling procedures were used in INS_4 and INS_7 - INS_10. For INS_4 - INS_7, the mister was activated for ten minutes after completion of the heat-up phase. At the end of ten minutes, the fan and mister were shut off for seven minutes and then reactivated for another ten minutes. Total water misting time was approximately 17 minutes. For INS_8 - INS_10, the mister was activated continuously for a period of 11-16 minutes.

In addition to the variable of horizontal versus vertical approach, firefighting protective clothing and heat venting variables were also investigated. Personnel from a Navy Fleet Training Command, San Diego participated in INS_7.

8.3.1 RICER 2 Cooling

The horizontal cooling approach was generally more effective for overall cooling of RICER 2 than the vertical approach. Cooling using the vertical approach was used in INS_5a (Figs. A154 - A162) and INS_6 (Figs. A163 - A171). Cooling near the QAS WTS 1-84-2 resulted in good cooling at the aft end (Fig. A155 - A164) for the aft thermocouple string) compared to cooling of the forward string. Cooling in the horizontal approach was used in INS_4 (Figs. A145 - A153) and INS_7 - INS_10 (Figs. A172 - A213). The data show more uniform overall cooling of the entire compartment, both forward (Figs. A181, A192, and A203) and aft (Figs. A182, A193, and A204). Temperatures aft in RICER 2 generally rose to 60-65°C above the coolest temperature and leveled off (e.g., Fig. A193).

The water motor fan approach can be compared to the manual firefighting techniques described in Sections 8.1 and 8.2. For the vertical approach, the water motor fan mister (Figs. A154, A155, A163, and A164) provides more uniform cooling of the RICER 2 space than the garden hose (Figs. A109 and A110). Compared to the larger hose streams (Figs. A91 and A92), the water motor fan cooling characteristics were similar.

Deck cooling was generally more effective with the water mister in the horizontal position (Figs. A183, A184, A194, A195, A205, and A206) compared to the vertical attack (Figs. A156, A157, A165, and A166). The water motor fan was generally not effective in cooling the bulkheads in RICER 2.

Table 5. Boundary Cooling using Water Motor Fan with Mister

Test	Access[1]	Equipment	Dress[2]	Tactic[3]	Venting	Firefighter Stay Time (min.)	Total Water Used (L (gal))	Procedural Comments	Results/Comments
INS_4	H	WMF with TF10N	NA	Cont.	Via QAS 1-75-2	NA	483 (127.5) (mister) 4434 (1170) total	Discharge mister through QAWTD 2-81-4; 10 min. misting, 7 min. without misting; 7 min. with misting; 17 min. total with mister	Estimated 76 L (20 gal) residual water on R2 deck, 114 L (30 gal) on R1 deck at the end of the test; seems to positively affect B2 temperature
INS_5a	V	WMF with TF10N	NA	Cont.	None	NA	483 (127.5) (mister) 4461 (1170) total	Discharge mister in QAWTS 1-84-2; no venting; same sequence as INS_4	Condensed steam rained in CIC; lots of water on R2 deck, poor efficiency
INS_6	V	WMF with TF10N	NA	Cont.	Via QAS 1-81-2; 2 sections of duct connected from fan inlet to weather for fresh air supply	NA	483 (127.5) (mister) 4461 (1170) total	Repeat INS_5a with venting and fresh air makeup; same sequence as INS_4	CIC conditions much better, heat flux in CIC not as high
INS_7	H	WMF with TF10N	CV/RG/EN	Cont.	Via QAS 1-75-2	2 min. before water activ.; 3 min. water activ.	483 (127.5) (mister) 4461 (1170) total	Same activation sequence as INS_4; FTC personnel in R1 with fan	Could not stay long in area with coveralls due to conduction; very brief reentry; rain in R1 caused coveralls to get wet quickly; protection of bare skin important

NOTES:
1 H - Horizontal; V - Vertical
2 EN - Ensemble; RG - Raingear; CV - Coveralls
3 Cont. - Continuous water application; Int. - Intermittent water application

Table 5. Boundary Cooling using Water Motor Fan with Mister (Continued)

Test	Access[1]	Equipment	Dress[2]	Tactic[3]	Venting	Firefighter Stay Time (min.)	Total Water Used (L (gal))	Procedural Comments	Results/Comments
INS_8	H	WMF with TF10N	RG	Cont.	R2 via CIC QAS 1-81-2 and 1-84-2; R1 via QAS 1-75-2	3 min. setup + 13.5 min. cooling = 16.5 min. total	346 (91.3) (mister) 3195 (843) total	Smoke curtain at QAWTD 2-81-4; 13.5 min. continuous cooling	60% estimated tolerance capacity; flow reduced by kink in hose
INS_9	H	WMF with TF10N	RG	Cont.	No venting except at QAS 1-75-2	5 min. before water active; then 11 min. cooling; 16 min. total	371 (98) (mister) WMF = 3438 (907) total 1.9 cm hoseline = 205 (54)	Repeat INS_7 with RG instead of coveralls; smoke curtain at QAWTD 2-81-4; small hoseline used to cool firefighter during test; 11 min. cooling	80-85% tolerance estimated; DC gloves "hot"
INS_10	H	WMF with TF10N	CV	Cont.	No venting initially except at QAS 1-75-2, then vent CIC via QAS 1-81-2 and 1-84-2	4 min. setup; out after 5 min. of cooling (9 min. total stay time), then vent RICER 2 via CIC and reenter for an additional 2 min.	478 (126) (mister) 4408 (1163) total	Smoke curtain at QAWTD 2-81-4; Repeat INS_9 with coveralls; 16 min. continuous cooling time	Tactic – Do not stay in until maxed out; leave some tolerance for reentry

NOTES:
1 H - Horizontal; V - Vertical
2 EN - Ensemble; RG - Raingear; CV - Coveralls
3 Cont. - Continuous water application; Int. - Intermittent water application

Residual water on the deck at the conclusion of INS_4 was estimated to be approximately 76 L (20 gal). This was much less than that observed in the manual cooling exercises with the handlines. Efficiency was not as good for the vertical attack, INS_5a, where much more water was observed on the RICER 2 deck. This indicates that the spray discharge pattern was not as efficient for the vertical application. For the horizontal evolutions, the temperature in RICER 2 leveled off at approximately 80-100°C after which point no additional cooling was observed.

8.3.2 Clothing and Heat Stress

Clothing and heat stress were evaluated by varying the protection of the personnel at the scene and by selectively ventilating RICER 2 and the adjacent compartments. Heat flux data for the water motor fan tests are presented in Tables 6 and 7.

Table 6. Maximum Heat Flux in CIC Overhead During Vertical Cooling with Water Motor Fan

Test	Maximum Flux (kW/m^2 (Btu/ft^2-sec))	
INS_5a	7.4	0.65
INS_6	8.0	0.71

Table 7. Maximum Heat Flux in RICER 1 During Horizontal Cooling with Water Motor Fan

Test	Maximum Flux (kW/m^2 (Btu/ft^2-sec))	
INS_4	19	1.7
INS_7	17	1.5
INS_8	3	0.27
INS_9	9.5	0.85
INS_10	12*	1.07*
INS_10	3.3**	0.29**

* before venting
** after venting

For the vertical approach, INS_5a was conducted without ventilating CIC. Steam which came from RICER 2 around openings at the water motor fan condensed and rained down in CIC. In INS_6, CIC was vented via WTD 1-81-2 to weather. Fresh air

makeup to the fan was ducted to the fan inlet side from weather. The CIC temperatures (Figs. A160 and A169) and maximum overhead heat flux (Figs. A161 and A170) were about the same, but personnel on the scene reported a significant drop in the heat stress in CIC when the space was vented. This is observed in the duration of the heat flux in the CIC overhead. In INS_5a, there were several heat flux peaks with the activation and stoppage of the cooling evolution (Fig. A162). When CIC was vented in INS_6, the heat flux peaked and then subsided after the water motor fan was stopped at the conclusion of the initial attack (Fig. A170).

The reduction of heat flux to personnel is more obvious in the horizontal evolutions. In INS_4, INS_7, and INS_9, a horizontal evolution was conducted with no venting of RICER 2. The only venting of RICER was via the access, QAS 1-75-2. Temperatures in the overhead of RICER 1, near the FR 81 bulkhead in INS_4, approached 150°C, with chest-height temperatures on the order of 81°C (Fig. A151). Heat flux at the overhead was on the order of 9.5 - 19 kW/m^2 (0.85 - 1.7 Btu/ft^2-s). For tests where RICER 2 was vented via CIC (INS_8 and INS_10), the maximum heat flux at the overhead of RICER 1 was 3.0 - 3.3 kW/m^2 (0.27 - 0.29 Btu/ft^2-s) after venting. This is shown most graphically in Fig. 20, where the heat flux in RICER 1 is shown before and after venting of RICER 2 (via the CIC scuttles). Heat flux in RICER 1 dropped by a factor of about 3 after venting was initiated.

The effects of venting along with protective clothing options are evident in the observed firefighter stay times in RICER 1. For the no ventilation situations, stay time after initiation of boundary cooling ranged from 3 min. (INS_7) to 11 min. (INS_9). This wide range is a result of the different levels of personnel protection: in INS_7, personnel in coveralls could not stay long in RICER 1 due to hot condensate dripping from the overhead. Personnel from FTG San Diego used in INS_7 were also not as acclimated to the heat conditions as the test team firefighters. In INS_9, the use of raingear permitted a longer stay time compared to INS_7.

Where venting of RICER 2 was used, firefighter stay times ranged from 11 - 13.5 minutes. In INS_8, firefighters only worked to about 60 percent of their estimated total tolerance. It was found from these tests that stay time could be increased and time to complete exhaustion could be extended by taking short breaks from the cooling evolution. In other words, personnel were able to work longer if they did not stay in the compartment (RICER 1) until they were totally exhausted from heat stress. Rather, they could increase their overall tolerance to the situation by taking a rest at weather before they were totally worn out.

Protection of exposed skin was again found to be necessary, especially for situations where steam condenses and "rains" on personnel.

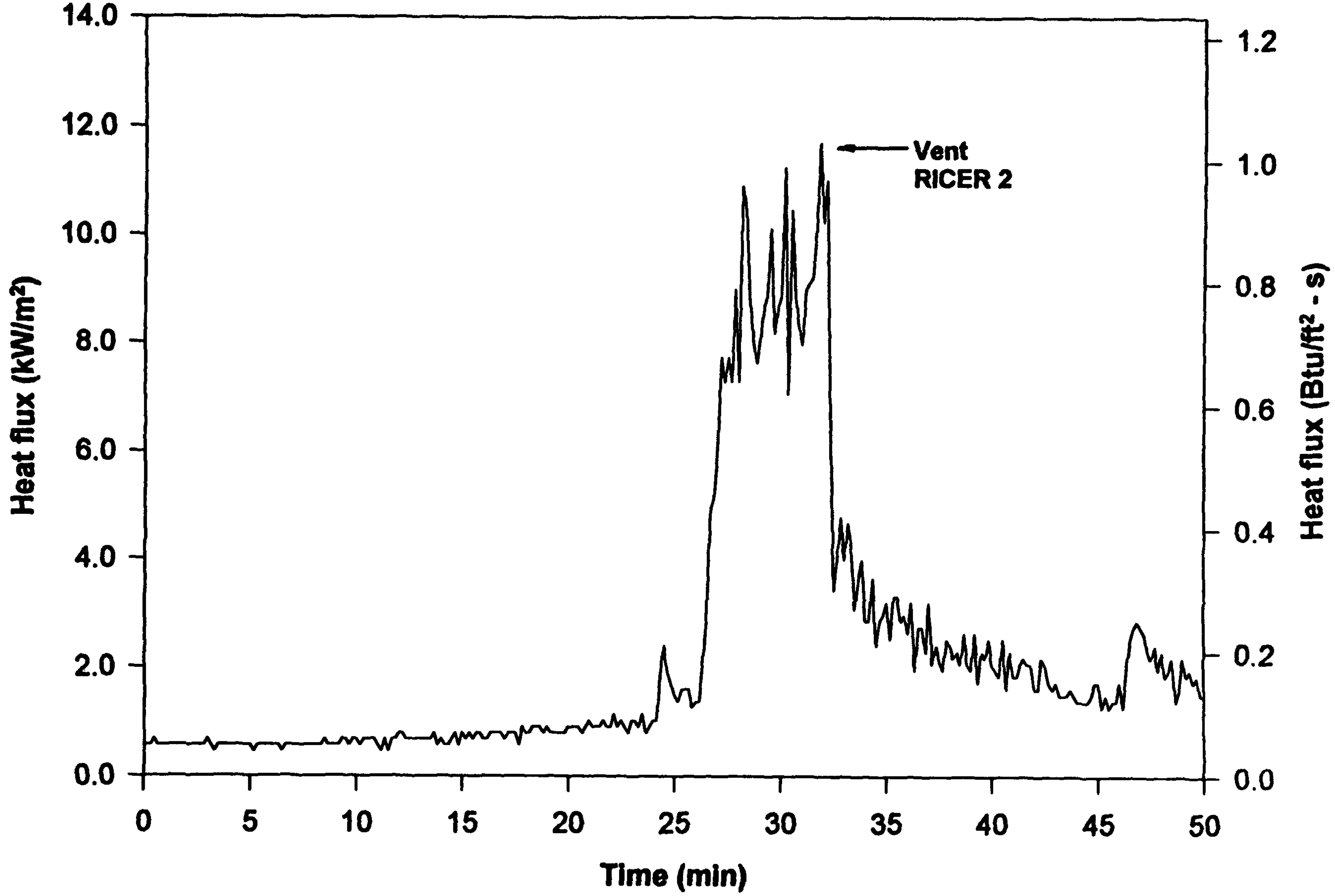

Fig. 20 - Effect of venting RICER 2 on RICER 1 heat flux, ins_10

9.0 DISCUSSION

9.1 Pressure Rise in RICER 2

Air pressure in RICER 2 was monitored in the overhead, near FR 81. Figure 21 shows the pressure rise for two of the more dramatic tests, both utilizing the Navy All Purpose Nozzle with 1.2 m (4 ft) applicator. In COL_6, a horizontal attack, a pressure rise of 1.0 kPa (0.15 psi) above ambient was recorded. This pressure rise was nearly tripled in COL_11, where a vertical approach was used. These pressure rises were recorded even though the RICER 2 space was not pressure tight, i.e., there were leaks from the cracked RICER 2 deck and through door gaskets and seals, particularly the doors opening to the well deck. The greater pressure rise was recorded in the vertical approach was probably a result of the smaller leakage area around the access hole, compared to the cracked door opening used in the horizontal approach. The APN created the greatest pressure spikes of all the devices tested.

9.2 Personnel Protective Gear – Gloves

Regardless of the clothing combination, the three locations most susceptible to burns were the hands, feet, and neck. There were two issues with the firefighter's gloves: ease of use during extended boundary cooling operations; and protection afforded by the firefighter's glove provided with the ensemble compared to the heat protective gloves and cotton gloves.

The Fire Fighter Ensemble has an integral knit wristlet in the sleeves for wrist protection. The FFE gloves have a waterproof vapor barrier and fire retardant liner as described in NSTM Chapter 077 [12]. The gauntlet provides wrist protection and is designed to be worn over the coverall sleeve as shown in Fig. 8 from NSTM Chapter 077. During tests COL_1 - COL_16, the firefighting test team found that greater protection from steam/hot water was afforded by tucking the glove <u>inside</u> the ensemble sleeve. Otherwise, the large cuff of the gauntlet tended to collect hot water dripping from the overhead and water dripping down the ensemble. With the glove tucked into the sleeve, the use of the integral sleeve knit wristlet was prevented. This procedure is in contradiction with the NSTM standard drawing and recommended procedure. Even with this precaution, the gloves were still one of the "weak links" which, in combination with the other heat stress factors, forced boundary cooling personnel to retreat.

The knit liner of the FFE glove was comfortable when the glove was dry, but when wet and hot it held the heat. (The analogy is the latent heat capacity of a hot potato—when hot it stays hot due to high moisture content and trapped steam inside the skin.) The liner came out when personnel rapidly removed the glove, e.g., when trying to cool down. It was extremely difficult to get the liner back into the glove so the glove could be used again. This could be remedied by securing the liner inside the FFE glove.[2]

[2] Since these tests, this modification has been initiated by NCTRF, Natick, MA.

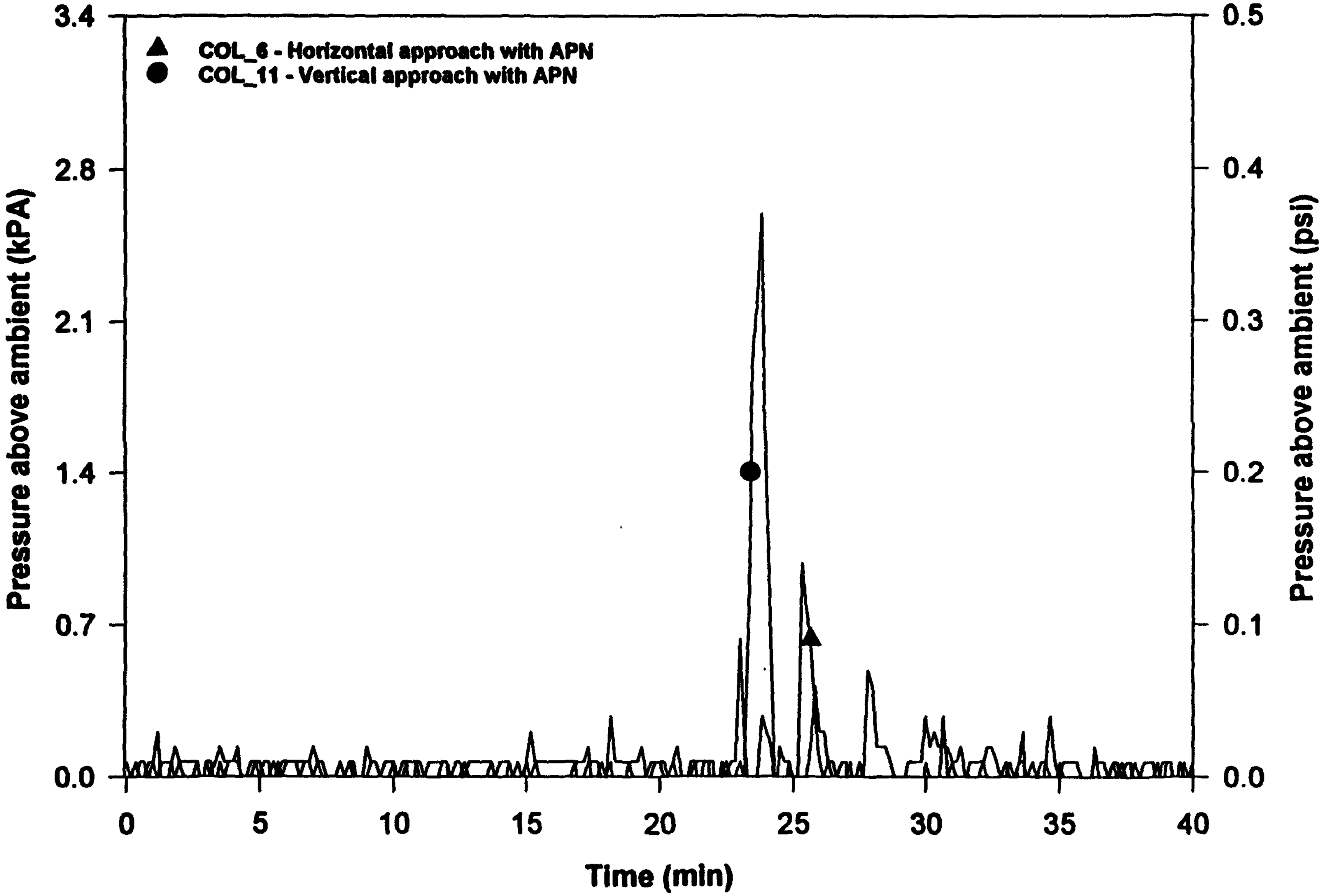

Fig. 21 - Pressure rise in RICER 2 as a result of indirect cooling using the Navy All Purpose Nozzle

During damage control evolutions, it is a common practice to attempt to sense the surroundings, i.e., hot bulkheads. When personnel are dressed in the ensemble, this leaves only one readily available means to expose the senses–the hand without the glove. Given the above difficulties, it is improbable that one will remove the glove knowing it cannot be put back on. Therefore, this vital information otherwise available would be lost.

Through the sixteen tests, problems were experienced with the gloves getting hot, wet, and "steaming" the hands. As a test would progress, rising heat was felt in the gloves to the point where it became nearly unbearable. At that point, the hands were cooled with a water spray. Once wet, the gloves had to be cooled much more often. The gloves were also saturated with hot water raining from the overhead as it condensed from steam. This had important operational implications. Lead personnel, whether they are firefighting or setting fire boundaries, will usually realize the most heat, steam, and hot water. As such, their hands get hotter faster. Still, other than for the nozzleman who has control of the water spray, there is no ready relief available. The noise and focus of effort by the nozzleman may prevent recognition of the agony being suffered by hosemen. In other words, the odds are that when the hands of tenders are "steamed," the hose team will have to retreat.

The experience from these boundary cooling tests showed that there was little difference in the ultimate protection realized with the plain cotton work gloves and the FFE gloves. The FFE gloves give far more protection against dry and extreme heat, such as when personnel touch hot metal. This is inherent in the design as stated by NSTM 077, Section 4.3.3.4., "The FFE gloves protect against abrasions, short duration flame (flash) exposure, and heat." While the FFE gloves took longer to get hot, they seemed to take much longer to cool. Alternately, the damage control heat protective gloves and cotton work gloves provide less protection against direct heat. Firefighter's hands became hot faster, but cooled faster when water was applied. All gloves required approximately the same frequency of re-cooling.

Data in the literature supports the observations in these tests. Leather gloves with and without a moisture barrier were evaluated against radiant and convective heat threats [13]. Tests were conducted with dry and wet gloves. It was found that, for radiant heat threats (2.3 cal/cm^2-s) involving wet gloves, (1) time to reach threshold pain and burn temperatures was greater for material with a vapor barrier compared to material without the vapor barrier; and (2) time to cool was greater for the material with the vapor barrier. For the tests involving wet gloves exposed to a conductive heat exposure (500°C under 0.28 kg/cm^2 pressure), it was found that time to threshold pain and burns was greater for the material without the vapor barrier. In the dry glove tests, materials with the vapor barrier provided increased protection in both the radiant and conductive tests but again took longer to cool in the radiant exposure tests.

Personnel on ex-USS SHADWELL found that the heat resistive gloves (stocked in DC lockers) fit poorly. In particular, the fingers were too short. Navy personnel from FTG San Diego on hand for Test INS_7 also described problems with these gloves. In particular, they indicated that these gloves became very slippery when wet. A

commercially-available firefighter's glove, Firecraft Model 80026 manufactured by Western Fire Equipment Co., was used in several tests and qualitatively found to be easier to use than the standard heat resistive glove. The Firecraft glove is a leather glove with a liner and Gortex vapor barrier.

10.0 CONCLUSIONS

(1) The greater the degree of protective clothing worn by an individual, the more aggressive boundary cooling tactics can be used. However, the more aggressive the tactic, the greater the ultimate heat strain on the individual.

(2) Twenty to thirty minutes was the maximum stay time in these evolutions. Stay time for the aggressive vertical cooling evolutions was eight to 14 minutes, about half the time for the horizontal evolutions. Stay time for horizontal evolutions with the water motor fan mister, where substantial steam was created in the adjacent space, were on the order of 10 to 15 minutes, even where venting was provided. Personnel not acclimated to high intensity heat stress situations may have shorter stay times than experienced personnel.

(3) Personnel with coveralls, rubber soled shoes or boots, and a hard hat can effectively cool boundaries. Head protection is required to protect against hot, dripping water from steam condensation.

(4) Water should not be applied to a hot boundary unless there is an imminent fire spread hazard. Applying water for the sole reason to cool the boundary may create unnecessary steam which will ultimately reduce the stay time of personnel protecting boundaries.

(5) Except for aggressively cooling a deck from a vertical (overhead) position, the 1.9 cm (0.75 in.) garden hose was effective for boundary cooling. Equipment for this tool (e.g., air hose and pipe manifold) can be easily fabricated by the ship's force.

(6) For horizontal boundary cooling evolutions, the vari-nozzle was more effective and easier to use than the All Purpose Nozzle with the applicator.

(7) The vertical approach was generally more effective for cooling RICER 2 than the horizontal method when handlines were used. This trend was reversed for cooling with the water motor fan mister.

(8) Vertical boundary cooling evolutions are very difficult to perform without a vent path for the steam buildup. A continuous vertical attack without steam venting is an ineffective technique because of the substantial steam buildup.

(9) For vertical boundary cooling evolutions using an indirect method, the access hole must be larger for a vari-nozzle than for the situation where the All Purpose Nozzle is used. A hole up to 45.7 cm (18 in.) may be required for a vari-nozzle with a pistol grip. It is easier to extend the APN with 1.2 m (4 ft) applicator down through an access hole and "work" the nozzle than it is with the vari-nozzle. Tactics are important; the nozzle spray pattern must be lower than any obstructions which might reduce spray reach/efficiency.

(10) As previously identified, the hands, wrist, neck, and feet are the "weak links" in terms of susceptibility to steam burns.

(11) Doors, hatches, and scuttles which are hot may require the use of a tool or device to open the closure without handling the hot steel. This may be true even if the accessman/boundary personnel are wearing the firefighters glove.

(12) In a horizontal approach, the water motor fan with mister is an effective cooling device. The cooling efficiency is high as demonstrated by the minimum amount of residual water. The water motor fan could be used unmanned. Its usefulness in the vertical approach is limited.

(13) Firefighting/boundary cooling personnel stay time is increased by providing a vent path for steam away from personnel. Stay time can also be increased by rotating personnel out of hot spaces for a rest before they are totally exhausted.

(14) Indirect boundary cooling can create pressure spikes in tight compartments as a result of rapid steam buildup.

(15) Current personnel protection allocation/use for the firefighter's ensemble (FFE) appears appropriate: it is worn by the nozzleman, hoseman, team leader, and access men in the repair party. While the FFE might be used by boundary cooling personnel, it is not absolutely required and other protective garment combinations may be used. The limitations of the current firefighter's glove design for hosemen needs to be emphasized. Heat resistive gloves currently in the damage control lockers would more likely be used by boundary cooling personnel.

(16) There is a need to emphasize the short water burst tactic for steam management when boundaries are very hot. If heat stress is not a factor, continual water application is acceptable for aggressively cooling boundaries (or extinguishing a fire). If heat stress is a factor (e.g., where there are large areas of exposed hot steel, then steam management is critical. The appropriate tactic is to let the steam rise and pass in the overhead after a short water burst. After steam has subsided, water application can then be continued.

11.0 RECOMMENDATIONS

(1) Doctrine and Tactics – Revise NSTM 555[3] to reflect the findings in this study. In particular, the following issues should be addressed:

(a) Modify the current doctrine to indicate that water should not be applied to a hot boundary unless there is an imminent fire spread hazard. In particular, modify the current doctrine, developed based on CBD tests [2], which recommends spraying boundaries for 15 seconds every minute. If the bulkhead or deck is so hot as to require cooling, initial bursts of water may be as short as 1-2 seconds. If this is the case, the steam production should be observed and application of further water adjusted so as not to generate more steam than is tolerable. The time and amount of water application will vary with conditions. Any boundary cooling operations should be preceded by options which make cooling unnecessarily, e.g., relocation or removal of combustibles.

(b) Emphasize venting of steam away from personnel during cooling evolutions.

(c) Emphasize the difficulties of vertical cooling approach evolutions.

(d) Discuss personnel stay times as a function of position (above or adjacent to incident), experience, and training. Emphasize that stay time may be increased by rotating personnel before they are totally exhausted.

(e) Emphasize that increased stay time can be achieved by locally cooling body parts. Specifically, once gloves are wet and the firefighter's pain threshold is reached, the gloves should be cooled with water. If hands are not cooled, the heat stress will ultimately contribute to reduce firefighter stay time. Care must be exercised in cooling hot personnel. If clothing is dry and so hot as to burn the person, initial wetting of the clothing may result in scalding. If clothing is already wet, additional water cooling will probably help a person experiencing heat stress.

(f) Headgear should be worn by boundrymen.

(g) Equipment options which are available for indirect cooling (e.g., vari-nozzle, All Purpose Nozzle) and considerations for using an indirect cooling approach (e.g., size of hole, protection against steam, potential for obstructions). Smoke blankets can be used to block steam around holes cut for indirect cooling. If possible, the metal cut away from a bulkhead or deck should be retained. This metal can be used to block the hole after the indirect attack is made and may be welded back into place to restore watertight integrity.

[3] Some of these revisions have been incorporated in the latest version of NSTM 555, dated 1 June 1993.

(h) There is a need for ships to preplan for indirect cooling (e.g., location) and venting of steam (e.g., vent paths). The effects of ambient wind on vent paths to weather must be considered.

(2) Firefighting Equipment
- (a) Retain some All Purpose Nozzles and four foot applicators on ships for use as an indirect cooling device.
- (b) Endorse the use of the 1.9 cm (0.75 in.) hoseline with garden hose nozzle for limited use in fire situations, e.g., boundary cooling, fire watch, and personnel cooling. Provide information to the Fleet on how they can fabricate the hose and a fire plug manifold for inclusion in repair lockers.
- (c) The water motor fan mister has potential for use as a cooling device. To potentially optimize the utility of the device, investigate its use for indirectly combating a Class A fire.
- (d) Identify equipment currently provided in repair lockers which could be used to access and open hot doors.

(3) Protective Clothing
- (a) Initiate an R&D program to develop a better firefighting glove.
- (b) Quantify the heat stress to firefighters. (Note: This was accomplished in Fleet Doctrine Evaluations which were a follow-on to ISCC testing.)

(4) Training
- (a) Provide training which incorporates realistic heat threats for indirect firefighting and boundary cooling.
- (b) Provide integrated training using a full repair party against a realistic heat threat so that heat stress and communications factors can be understood and experienced.

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13.0 ACKNOWLEDGMENTS

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Appendix A

Data

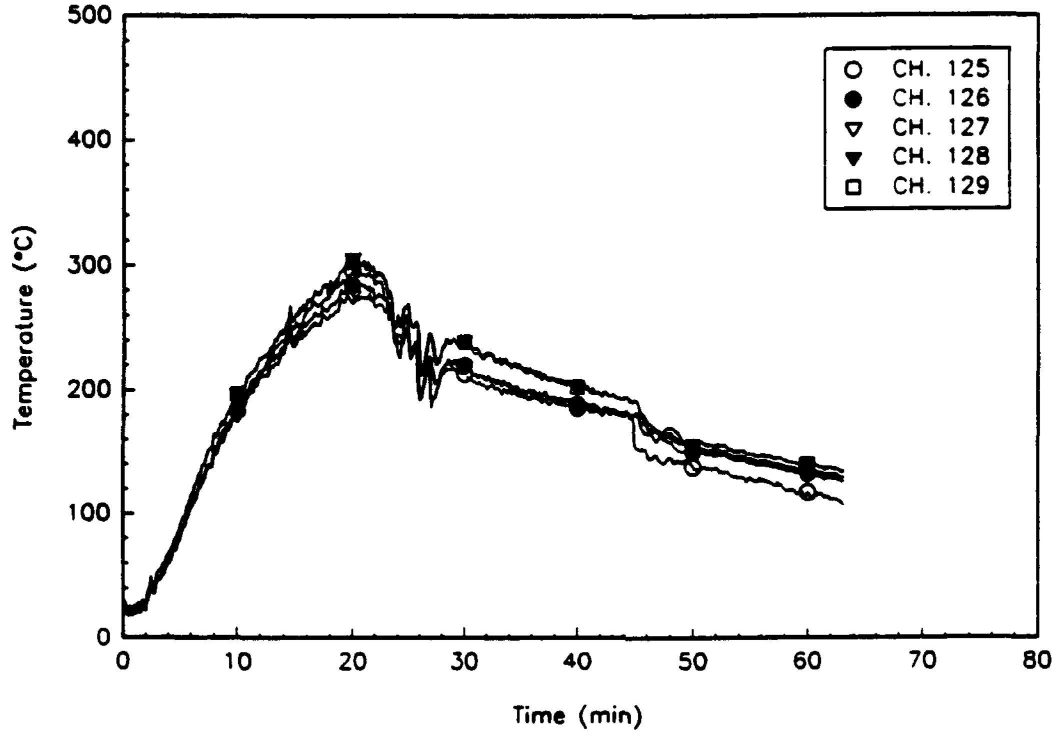

Fig. A1 – RICER 2 air temperature forward, COL_1

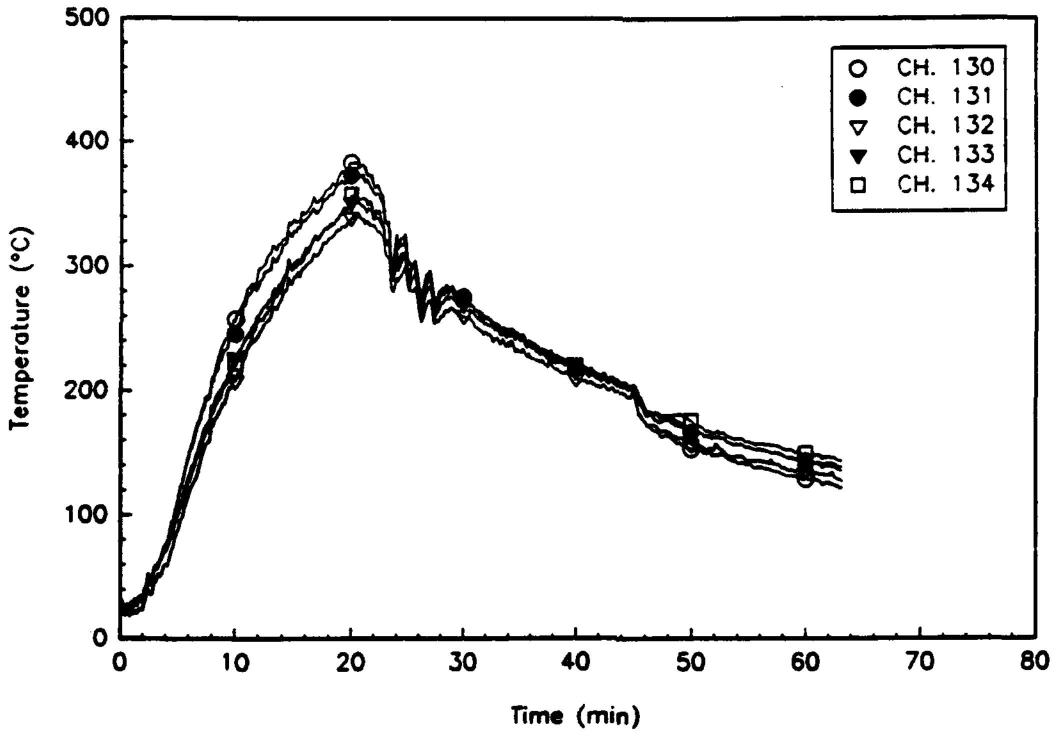

Fig. A2 – RICER 2 air temperature aft, COL_1

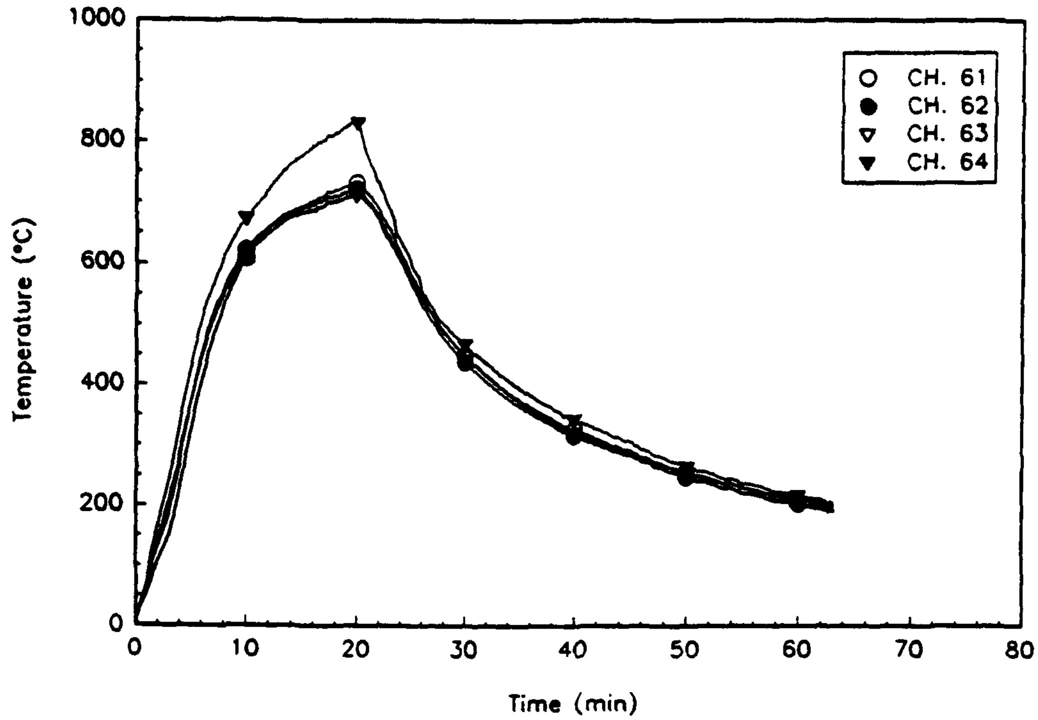

Fig. A3 – RICER 2 deck temperatures aft, COL_1

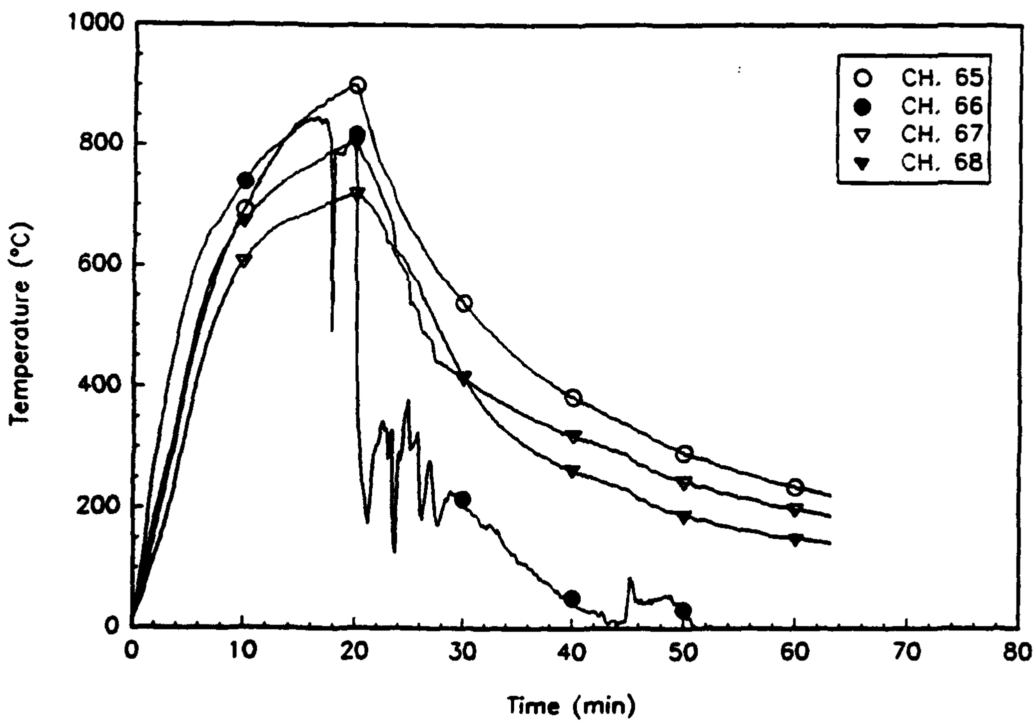

Fig. A4 – RICER 2 deck temperatures forward, COL_1

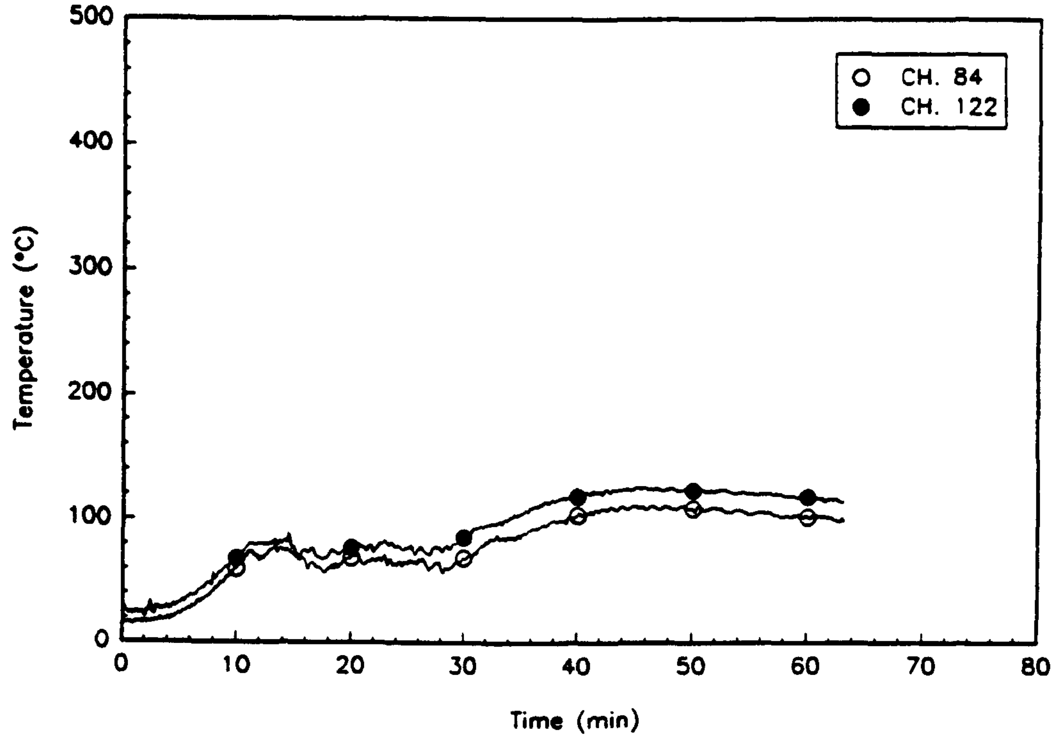

Fig. A5 — FR 81 bulkhead temperatures forward, COL_1

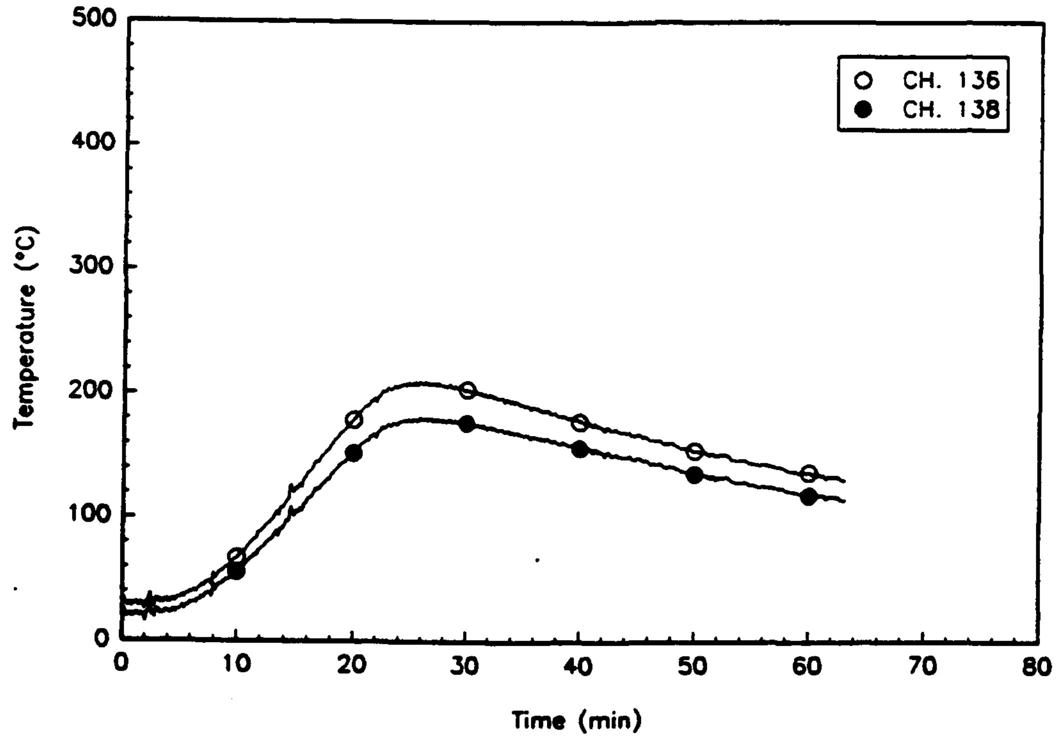

Fig. A6 — FR 88 bulkhead temperatures (RICER 2 side), COL_1

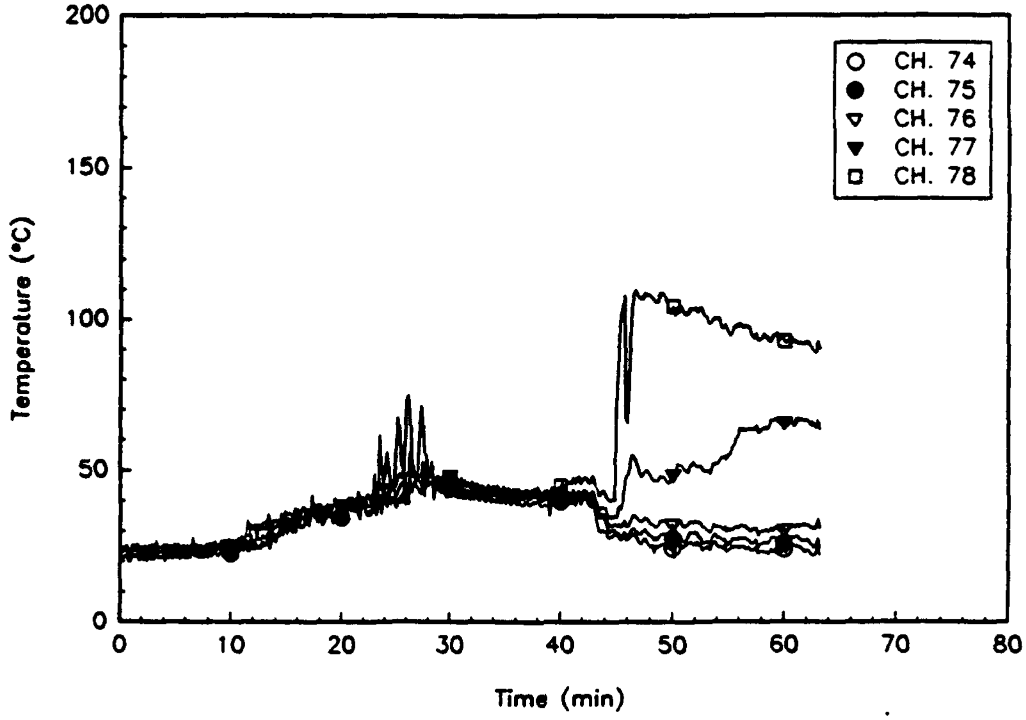

Fig. A7 – RICER 1 air temperatures aft, COL_1

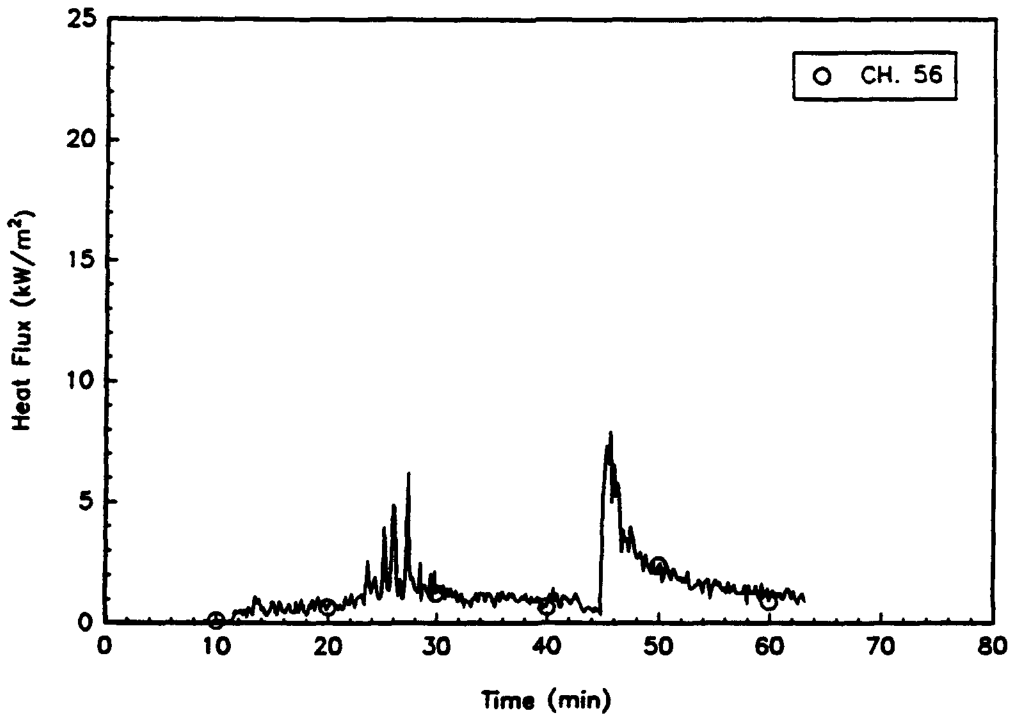

Fig. A8 – Total heat flux at RICER 1 overhead, COL_1

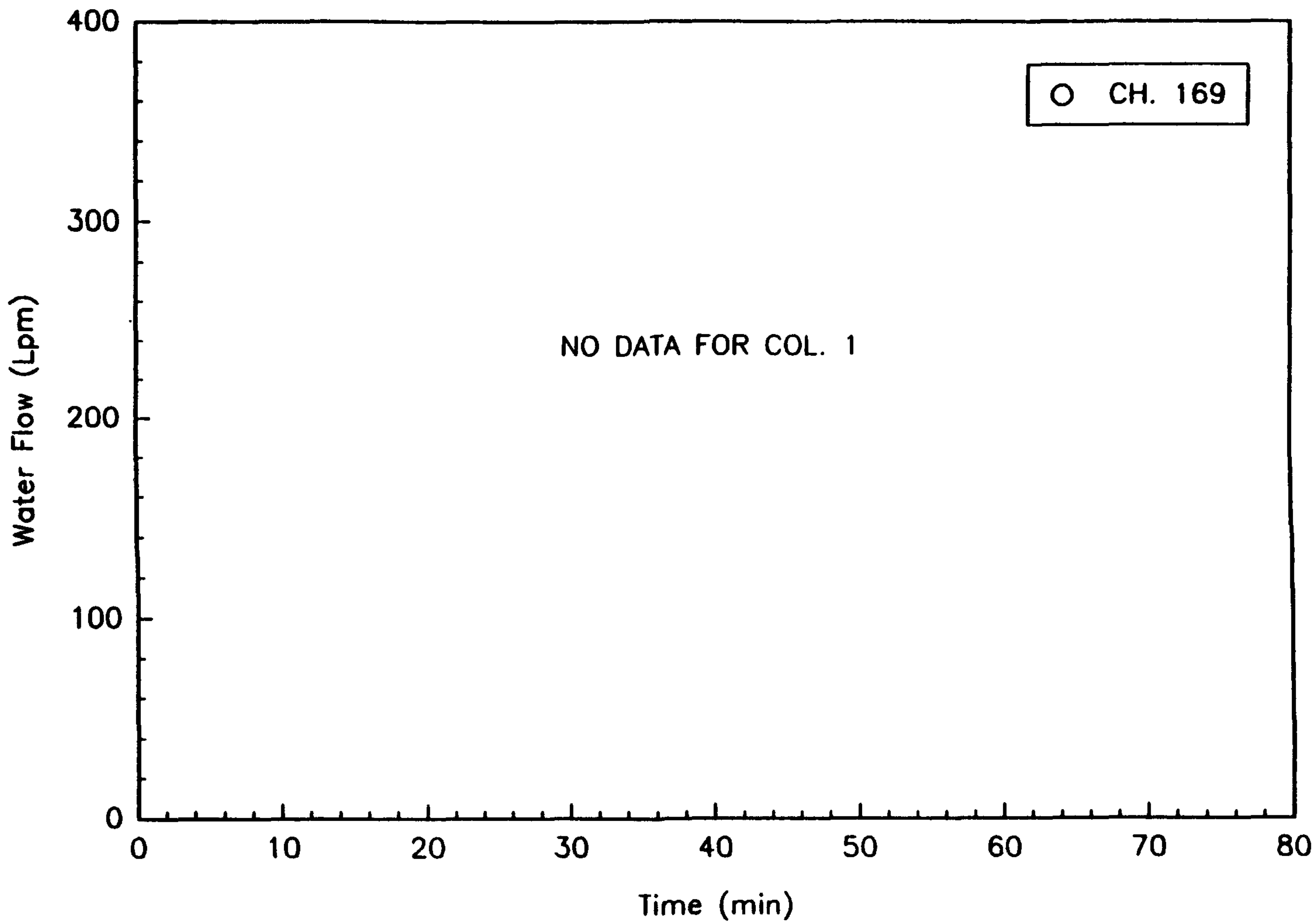

Fig A9 – Water flow from cooling handline, COL_1

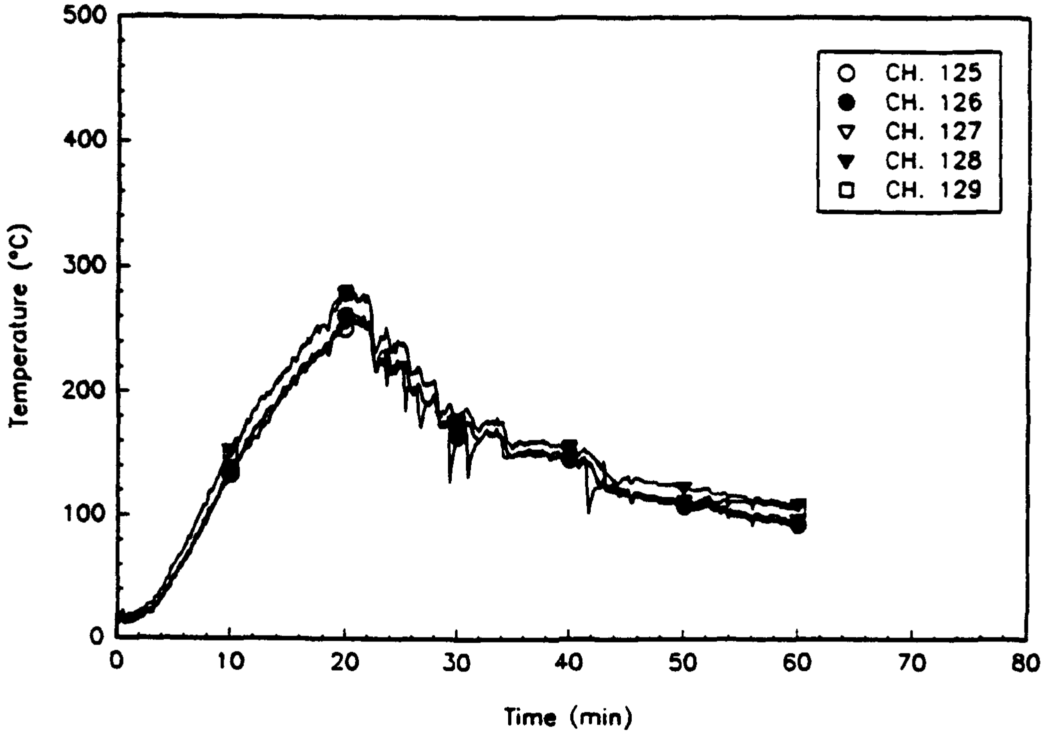

Fig. A10 – RICER 2 air temperatures forward, COL_2

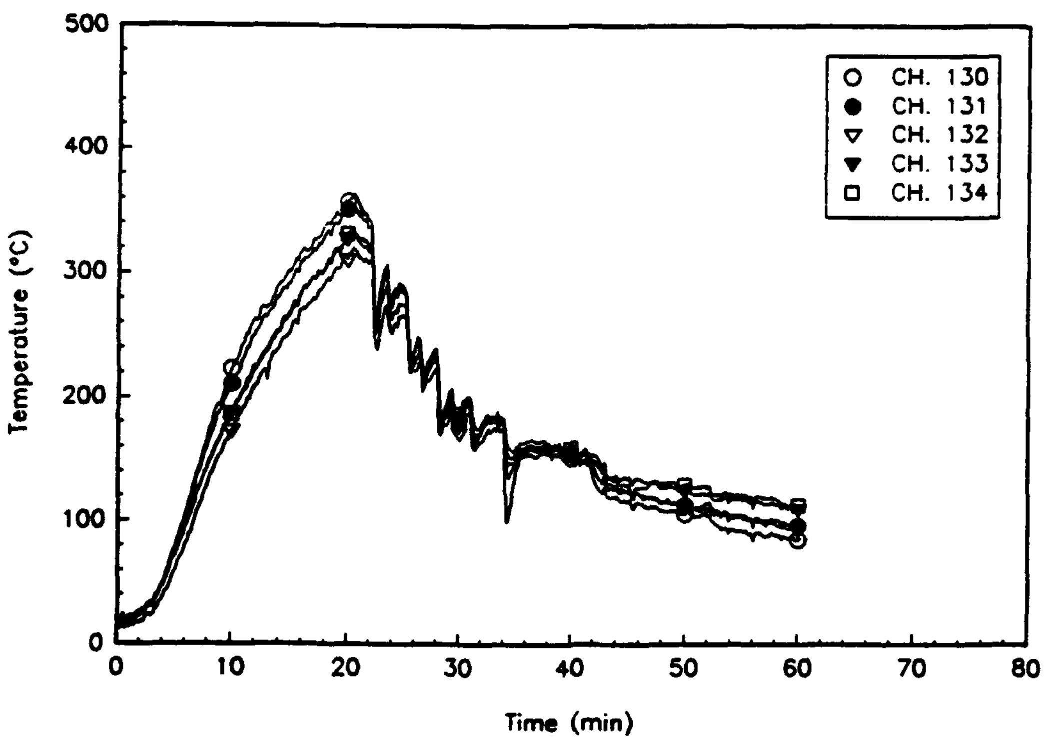

Fig. A11 – RICER 2 air temperatures aft, COL_2

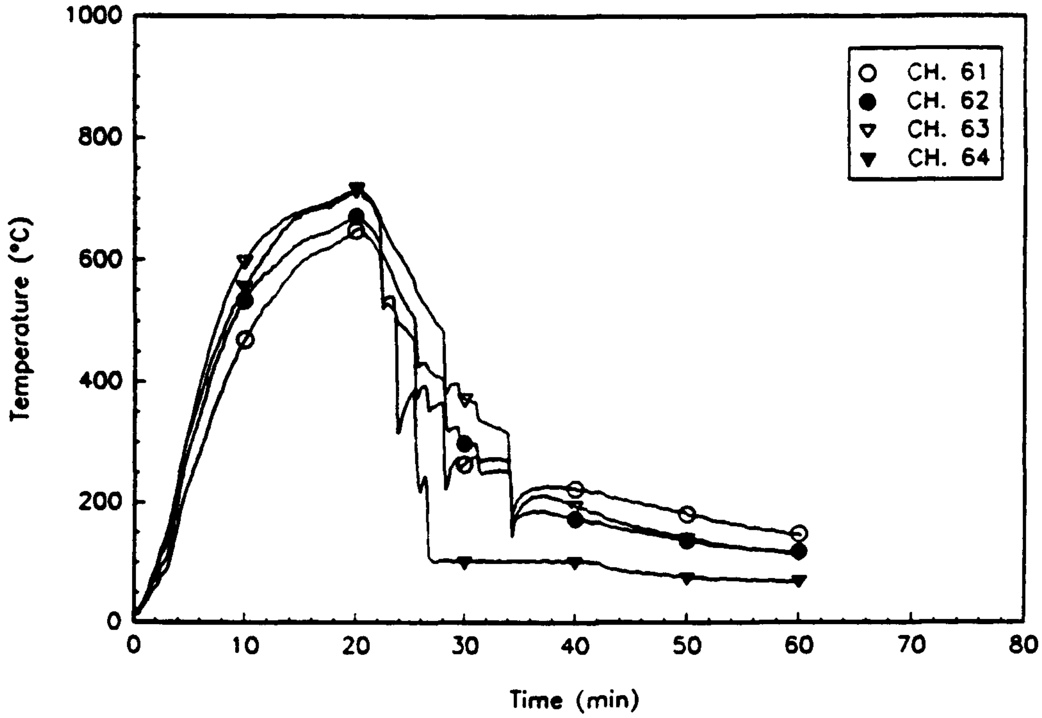

Fig. A12 – RICER 2 deck temperatures aft, COL_2

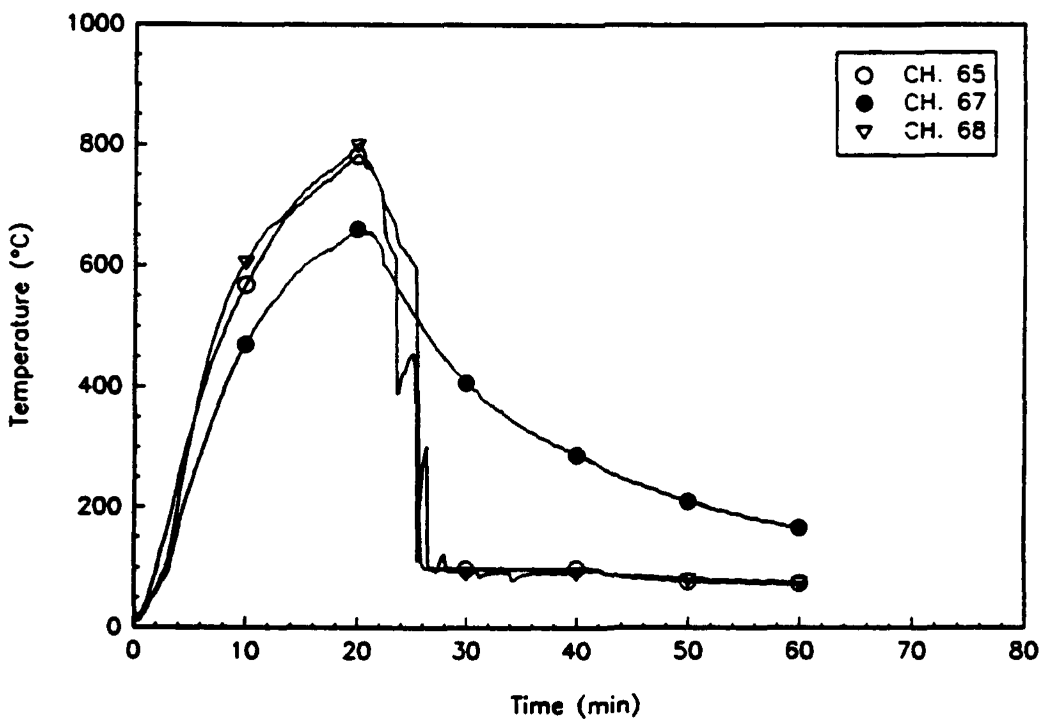

Fig. A13 – RICER 2 deck temperatures forward, COL_2

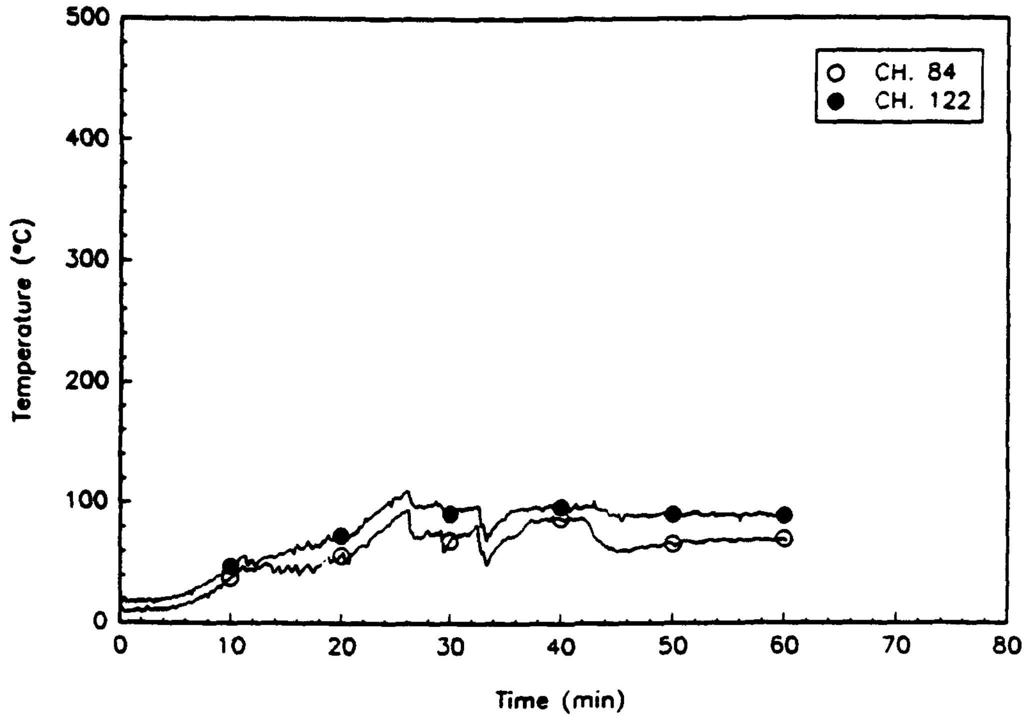

Fig. A14 – FR 81 bulkhead temperatures forward, COL_2

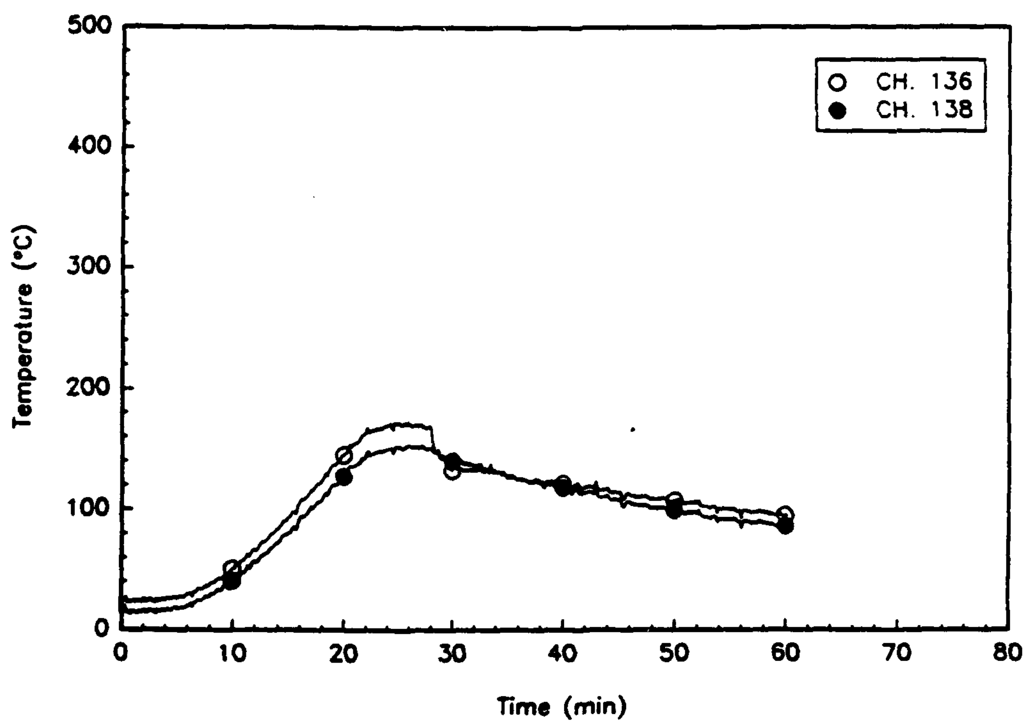

Fig. A15 – FR 88 bulkhead temperatures (RICER 2 side), COL_2

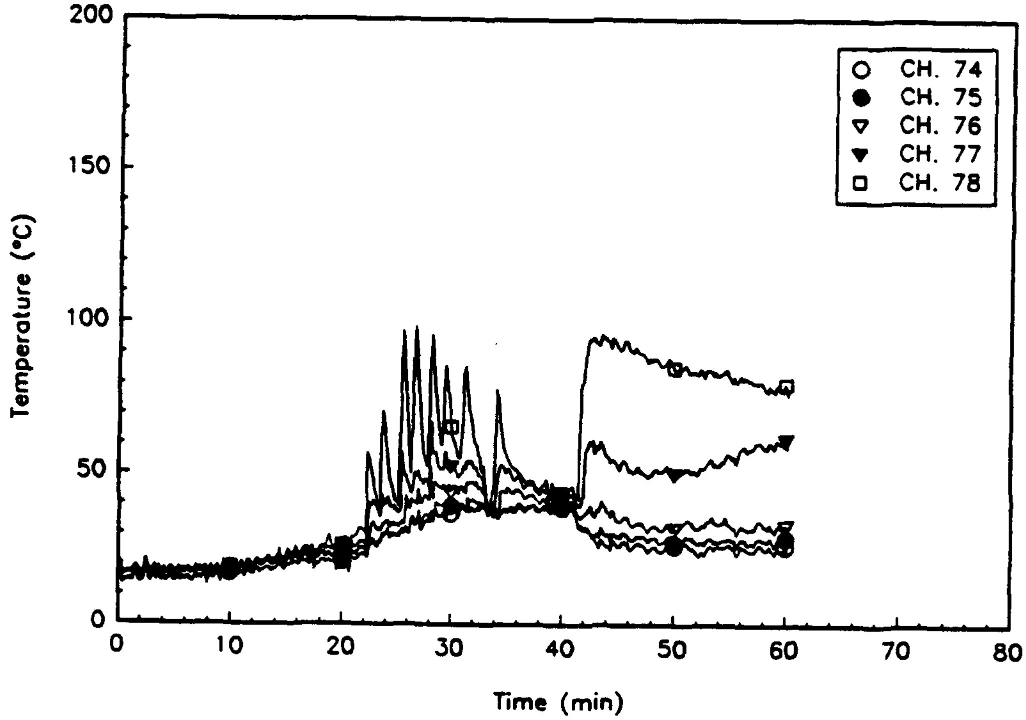

Fig. A16 – RICER 1 air temperatures aft, COL_2

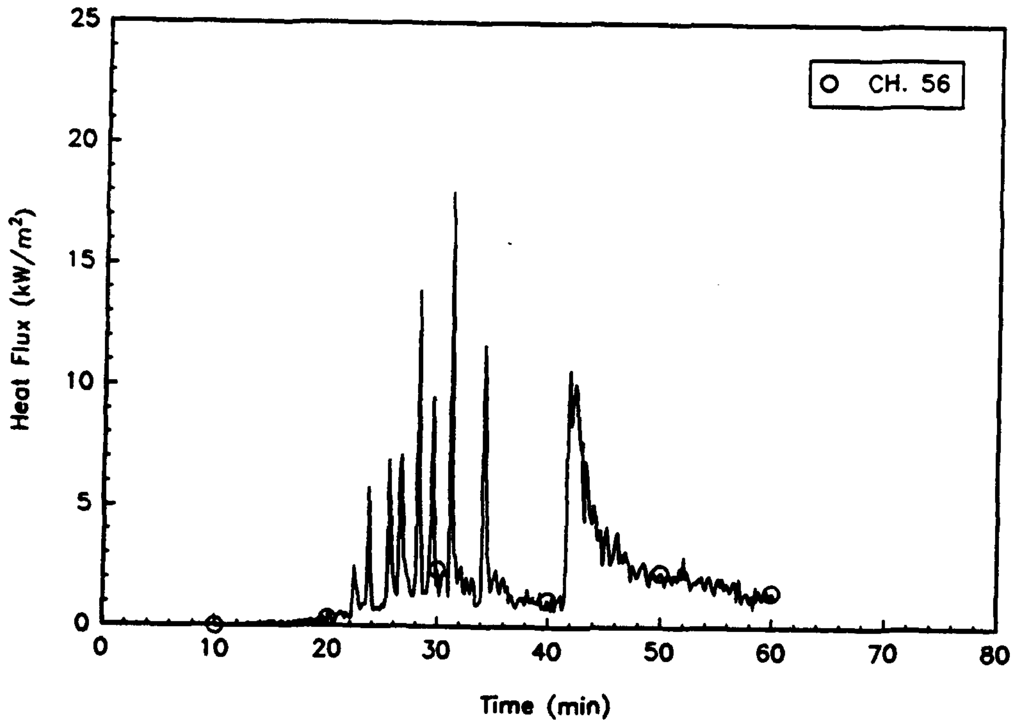

Fig. A17 – Total heat flux at RICER 1 overhead, COL_2

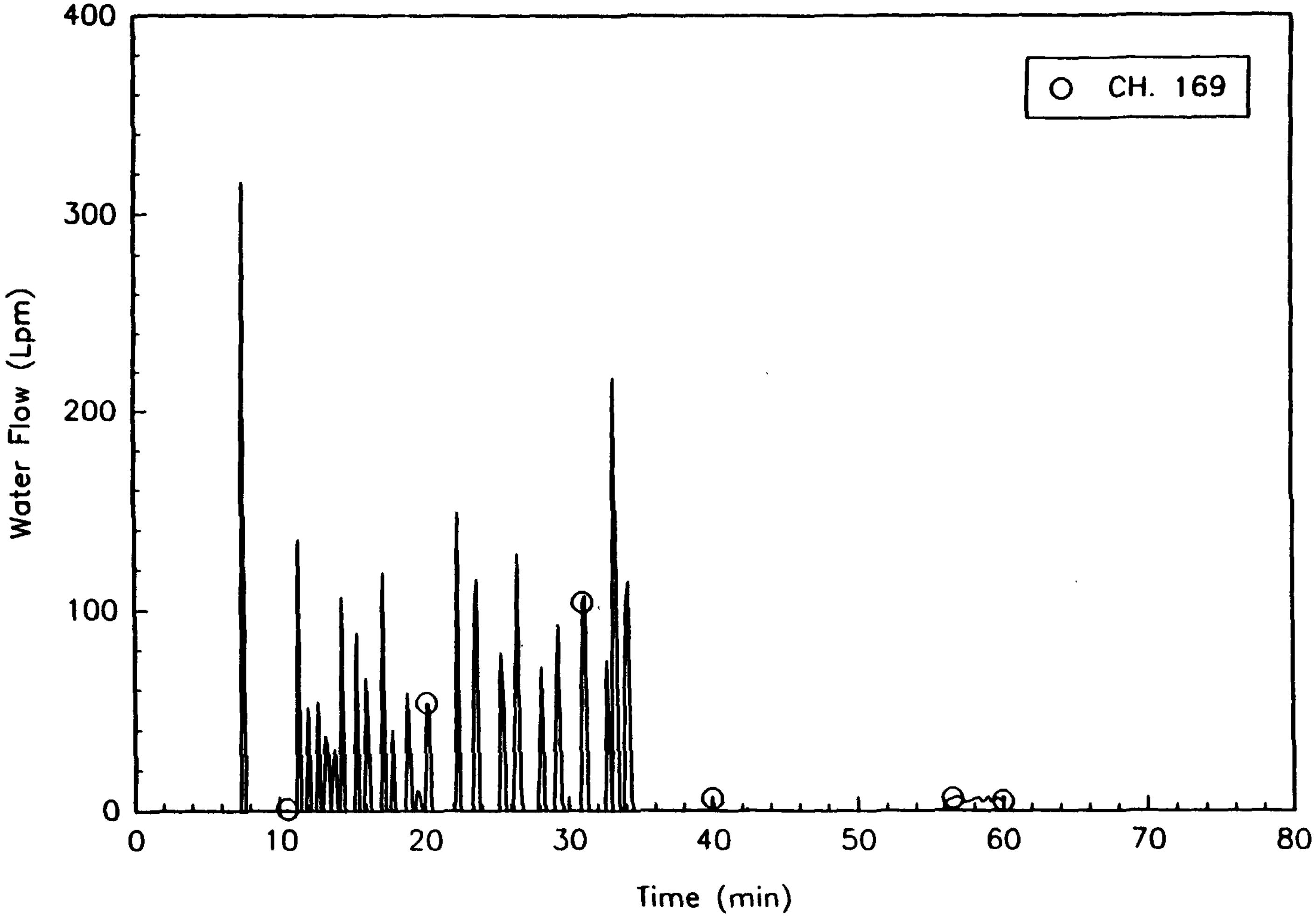

Fig. A18 — Water flow from cooling handline, COL_2

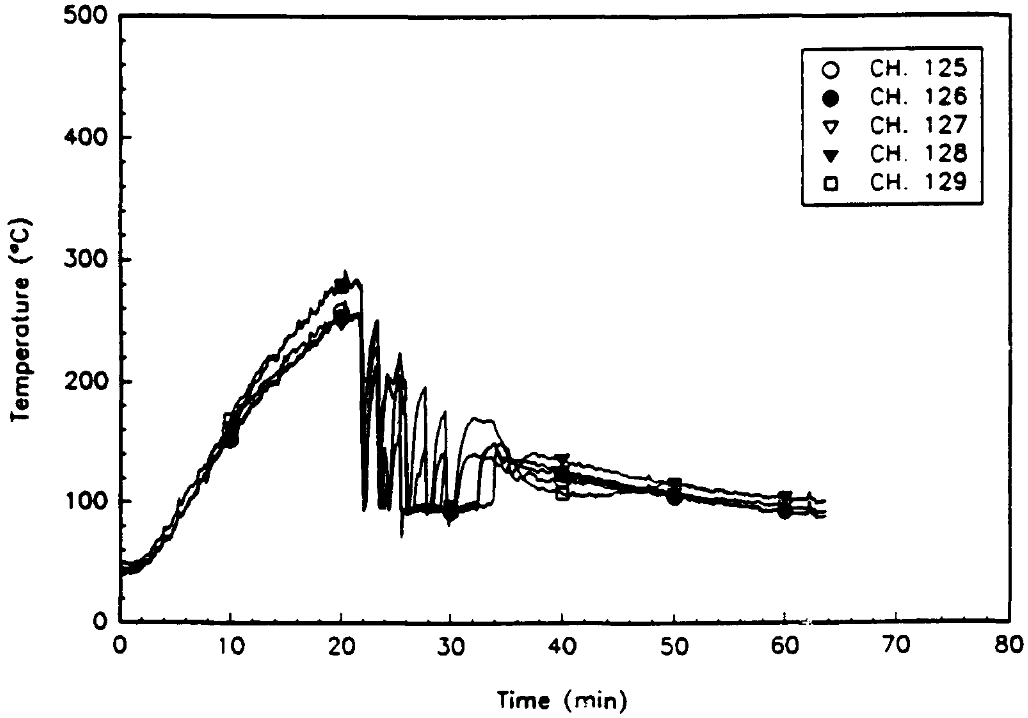

Fig. A19 — RICER 2 air temperatures forward, COL_3

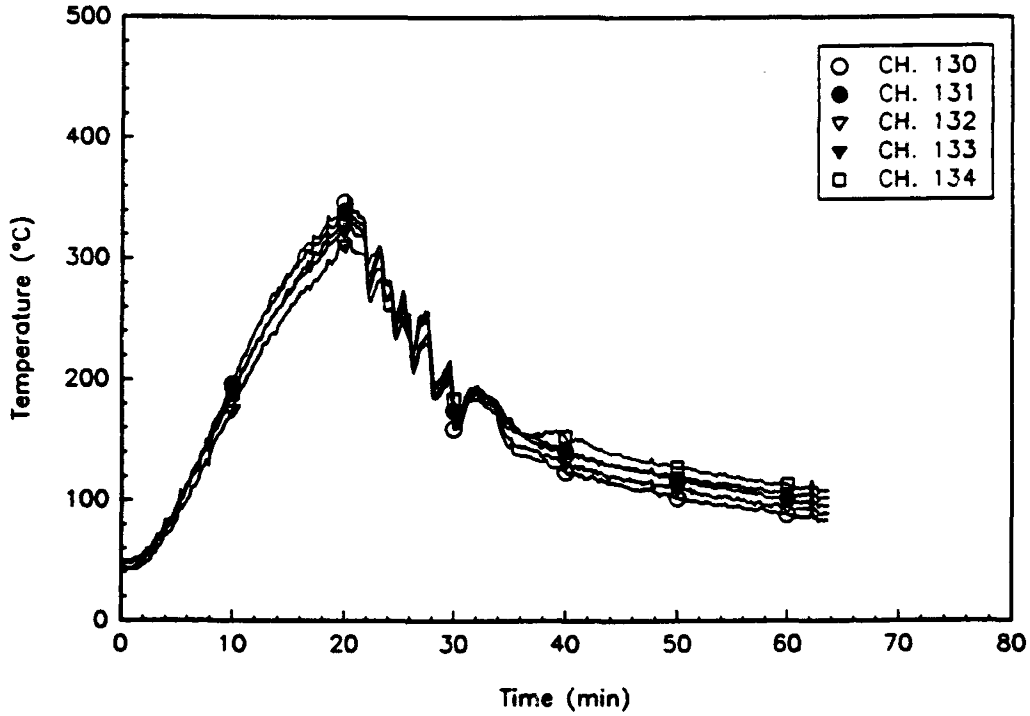

Fig. A20 — RICER 2 air temperatures aft, COL_3

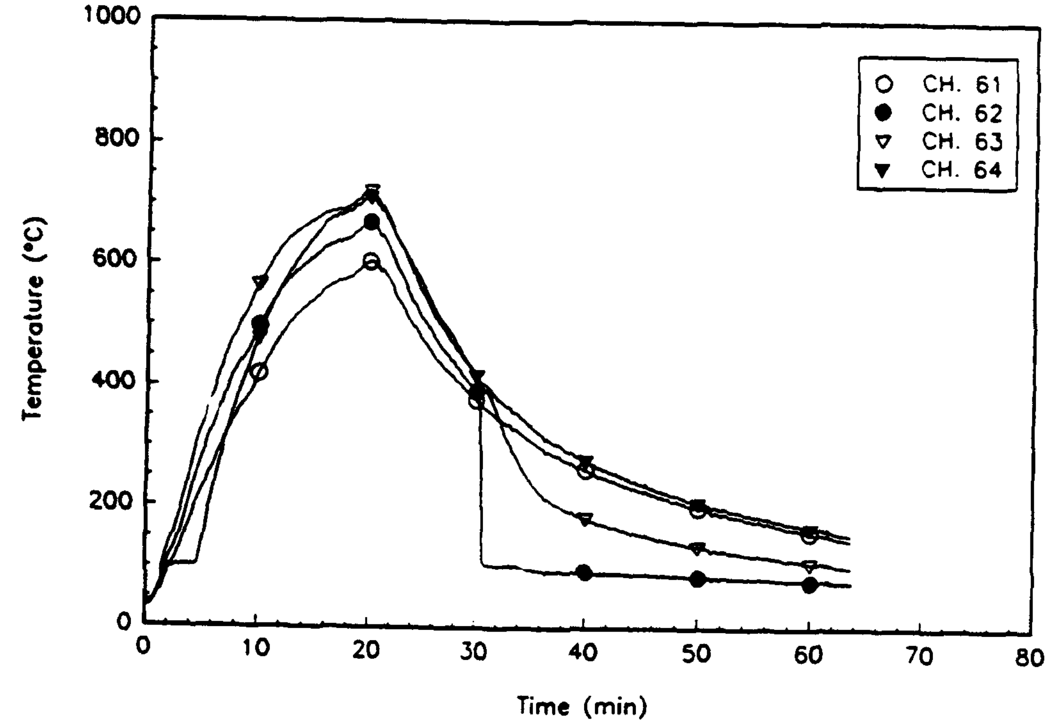

Fig. A21 – RICER 2 deck temperatures aft, COL_3

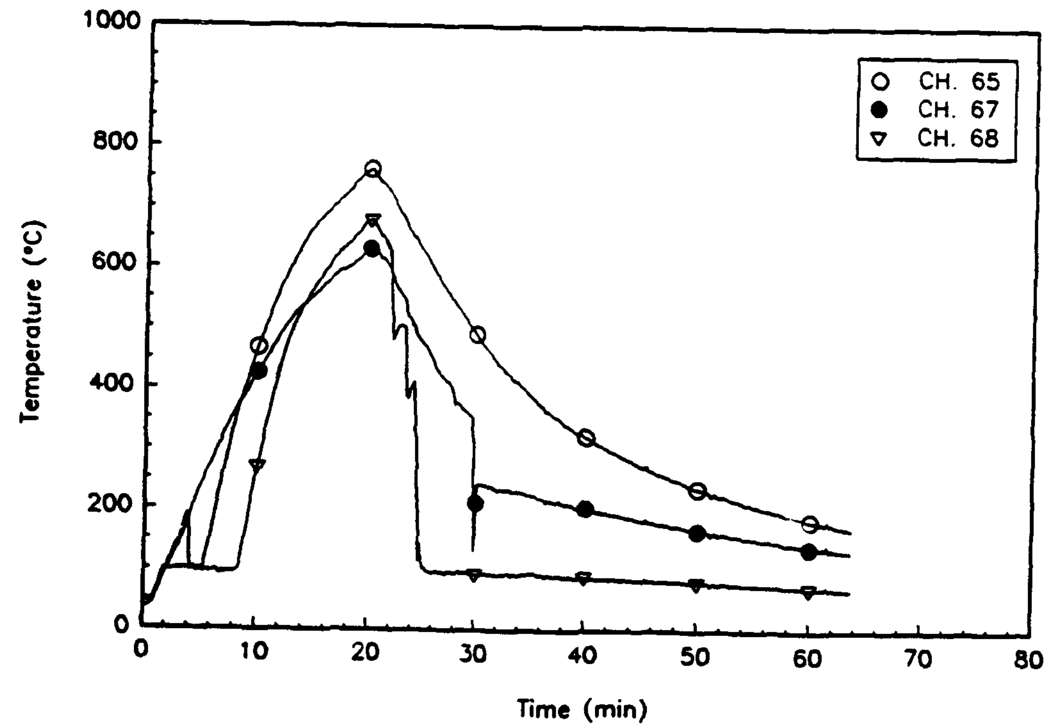

Fig. A22 – RICER 2 deck temperatures forward, COL_3

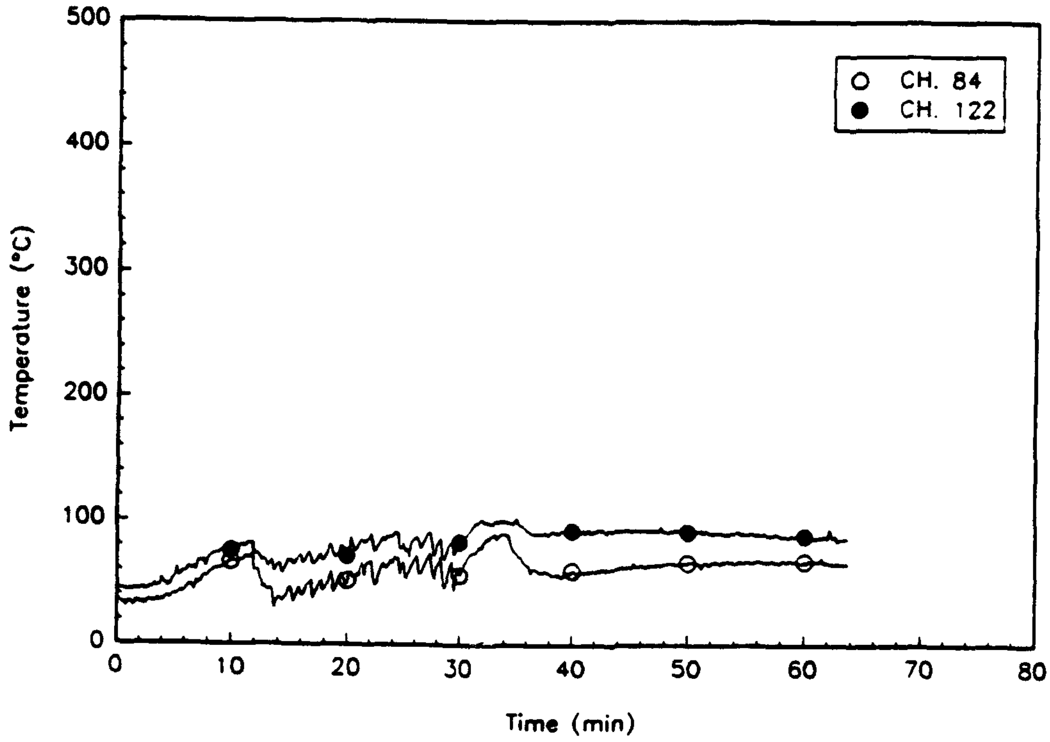

Fig. A23 – FR 81 bulkhead temperatures forward, COL_3

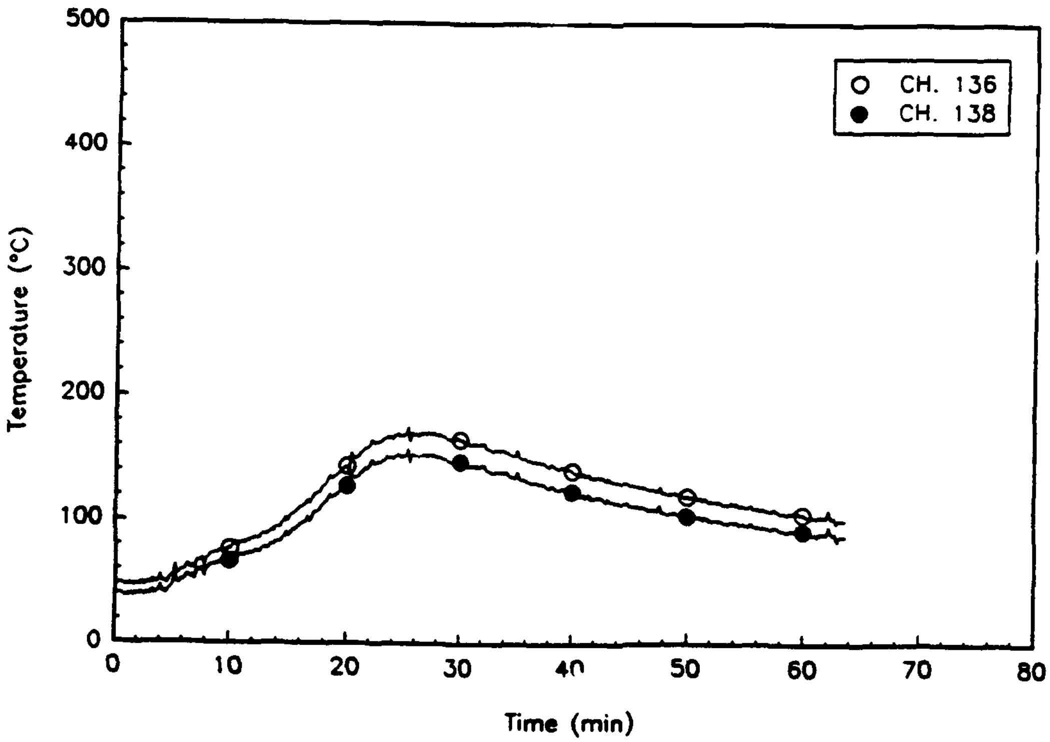

Fig. A24 – FR 88 bulkhead temperatures (RICER 2 side), COL_3

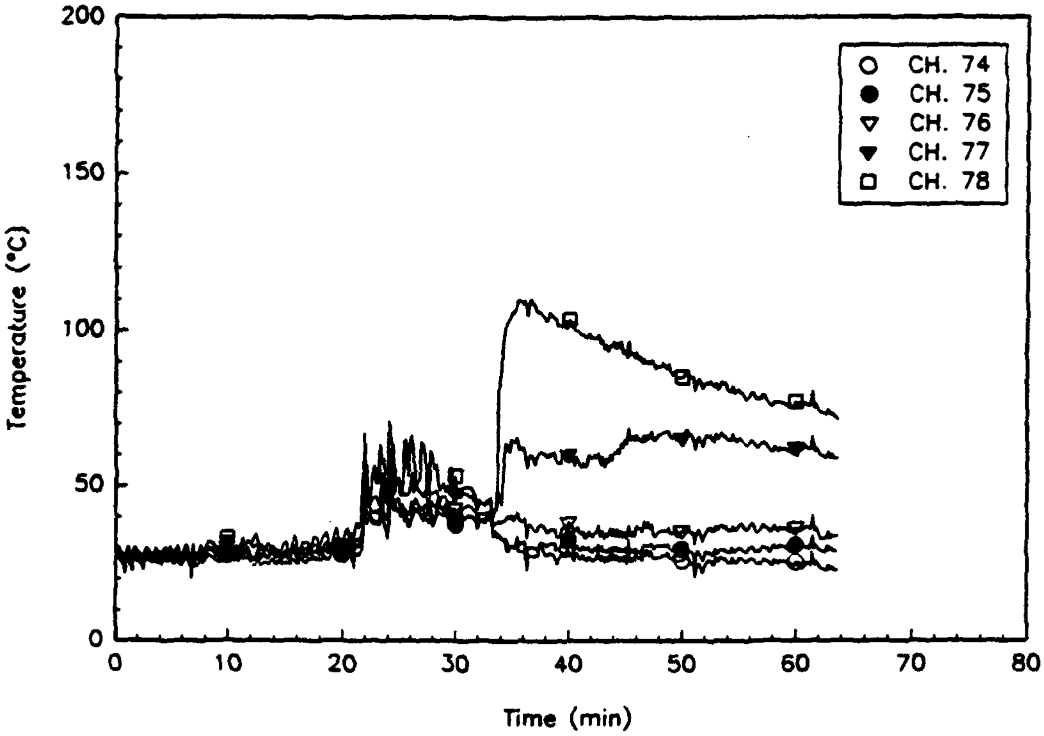

Fig. A25 — RICER 1 air temperatures aft, COL_3

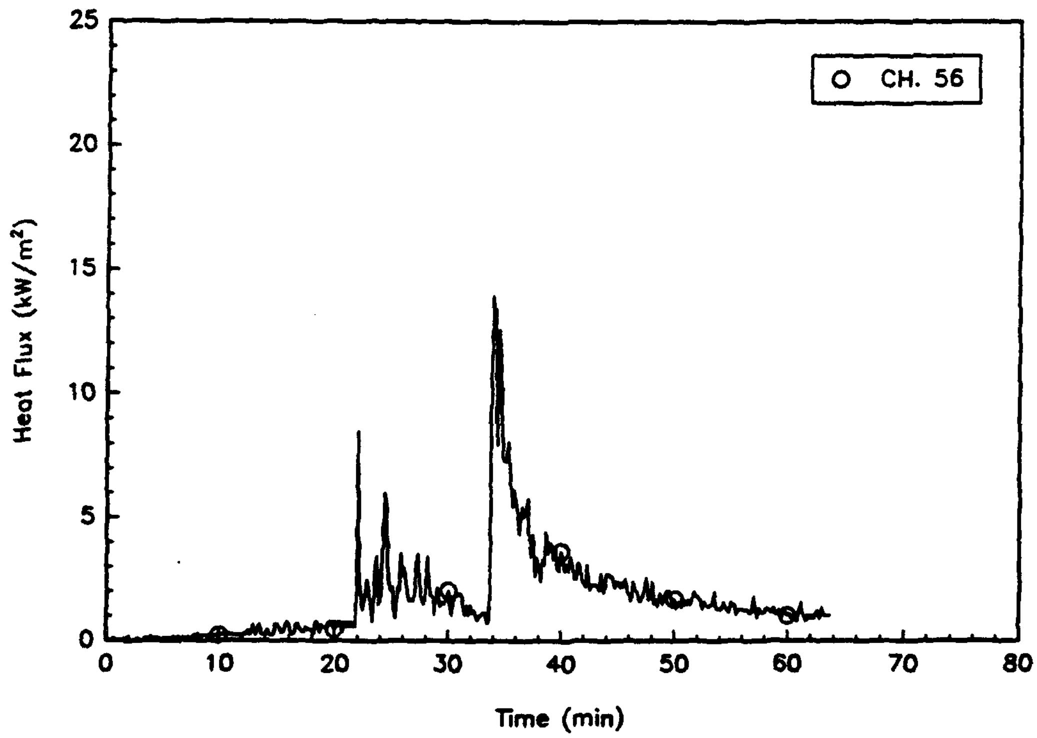

Fig. A26 — Total heat lux at RICER 1 overhead, COL_3

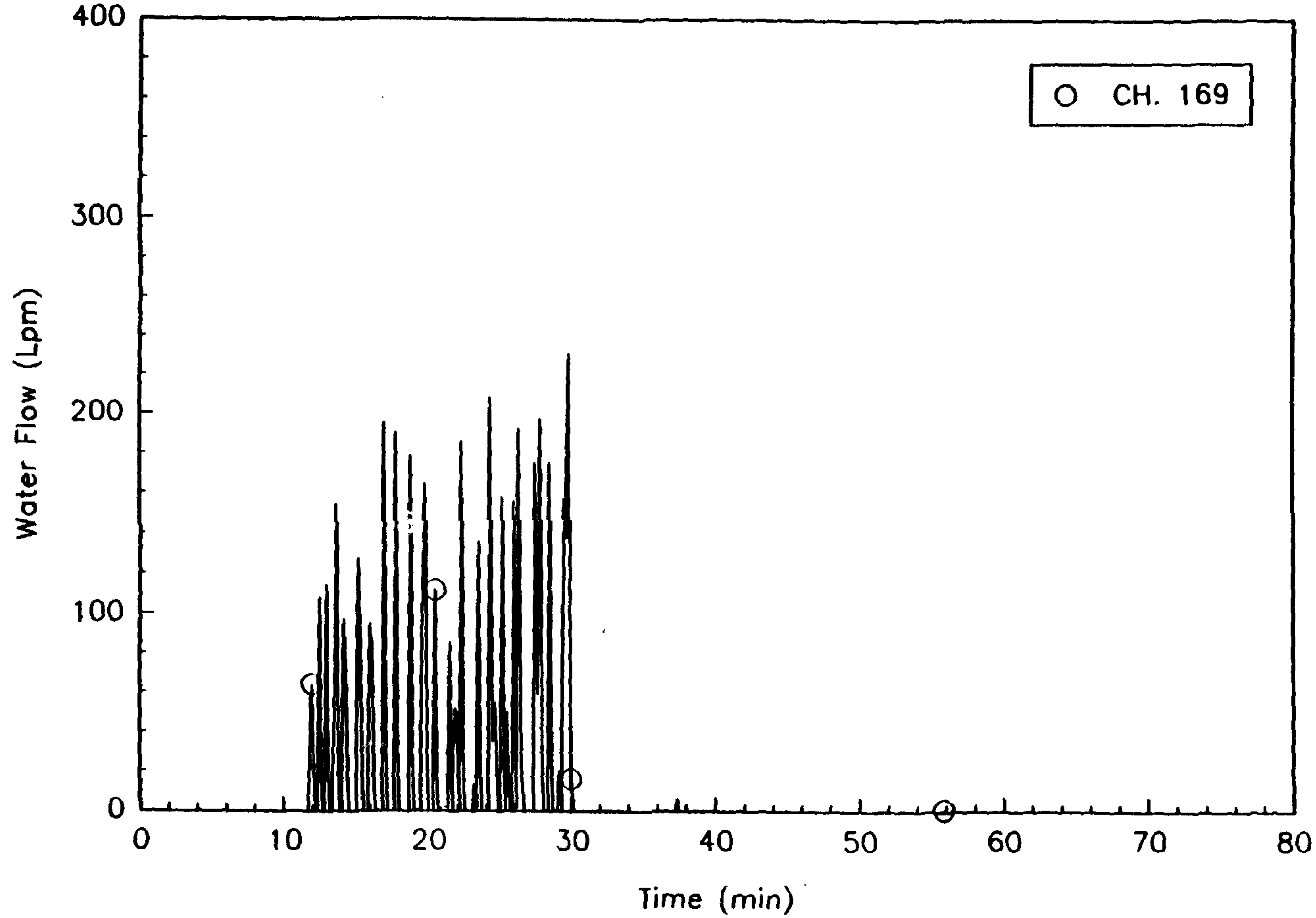

Fig. A27 – Water flow from cooling handline, COL_3

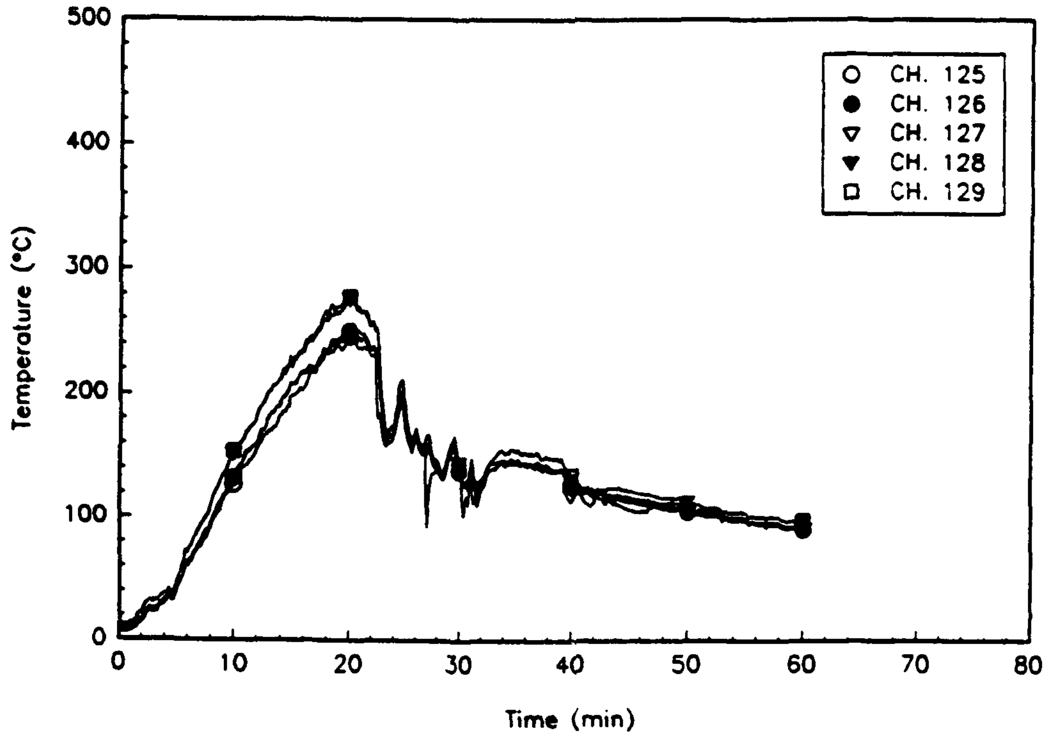

Fig. A28 — RICER 2 air temperatures forward, COL_4

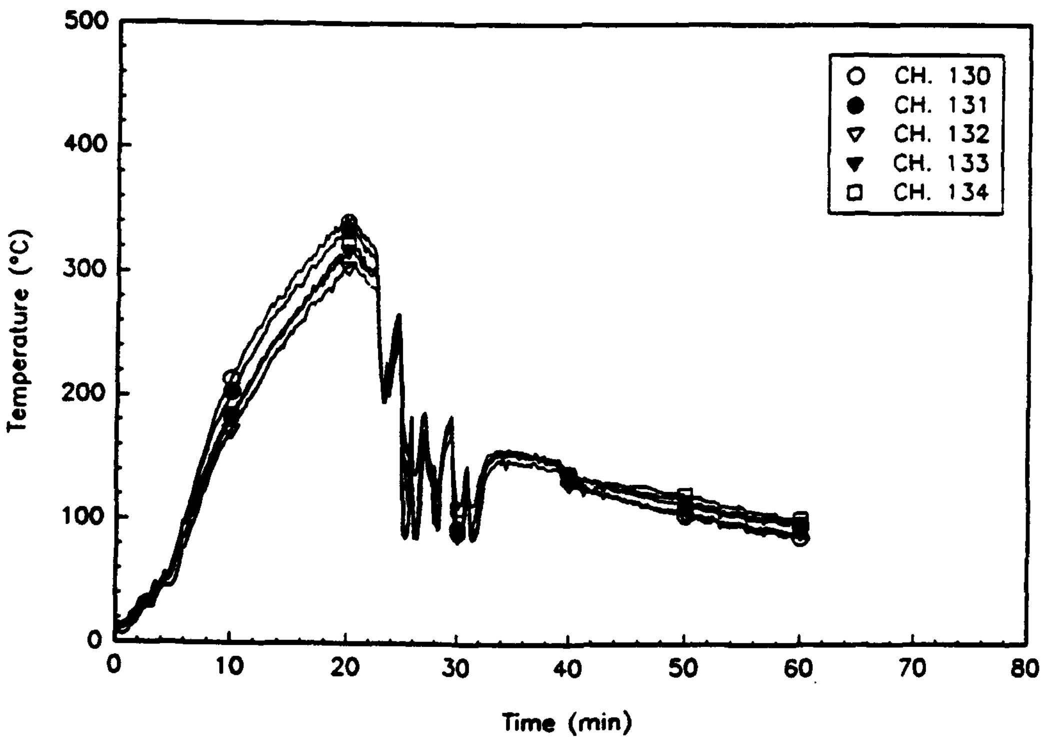

Fig. A29 — RICER 2 air temperatures aft, COL_4

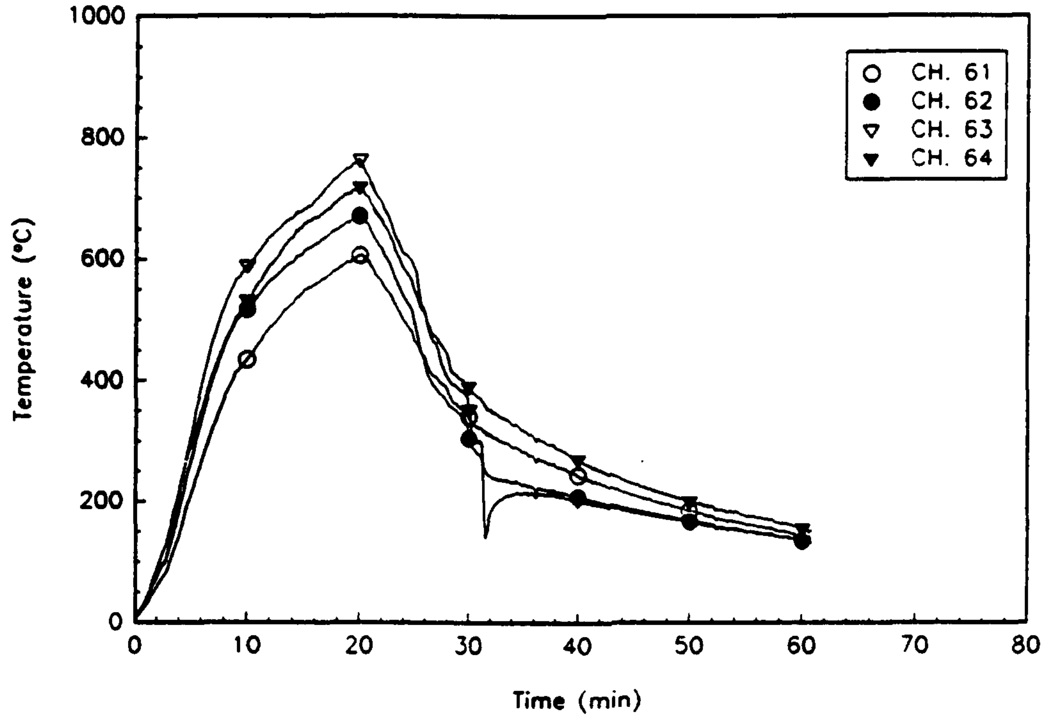

Fig. A30 — RICER 2 deck temperatures aft, COL_4

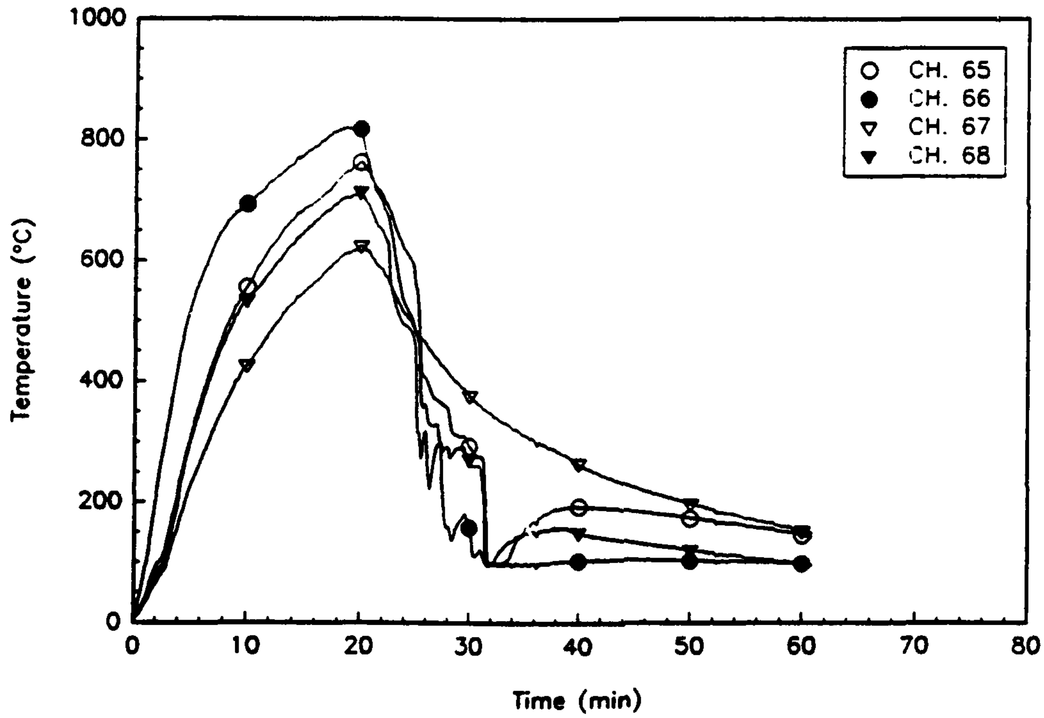

Fig. A31 — RICER 2 deck temperatures forward, COL_4

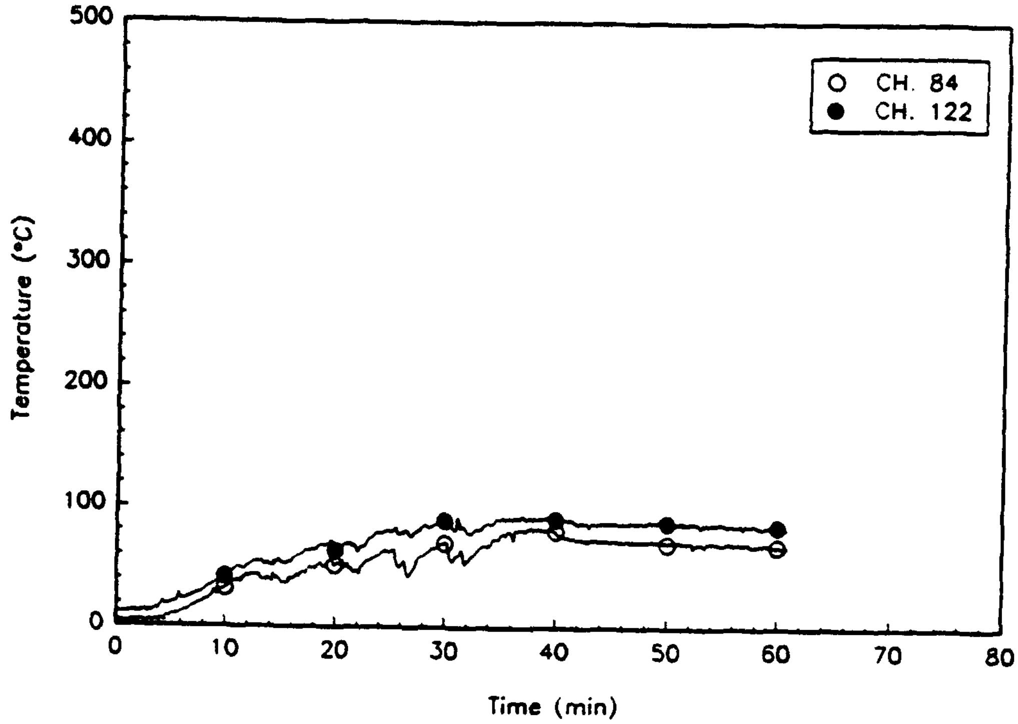

Fig. A32 – FR 81 bulkhead temperatures forward, COL_4

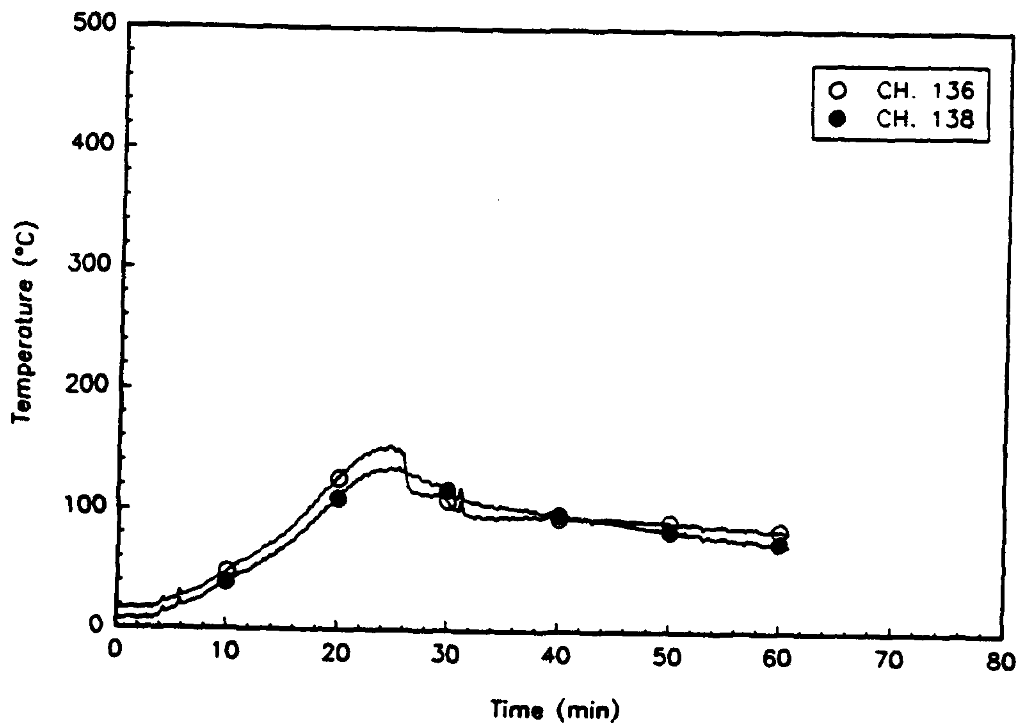

Fig. A33 – FR 88 bulkhead temperatures (RICER 2 side), COL_4

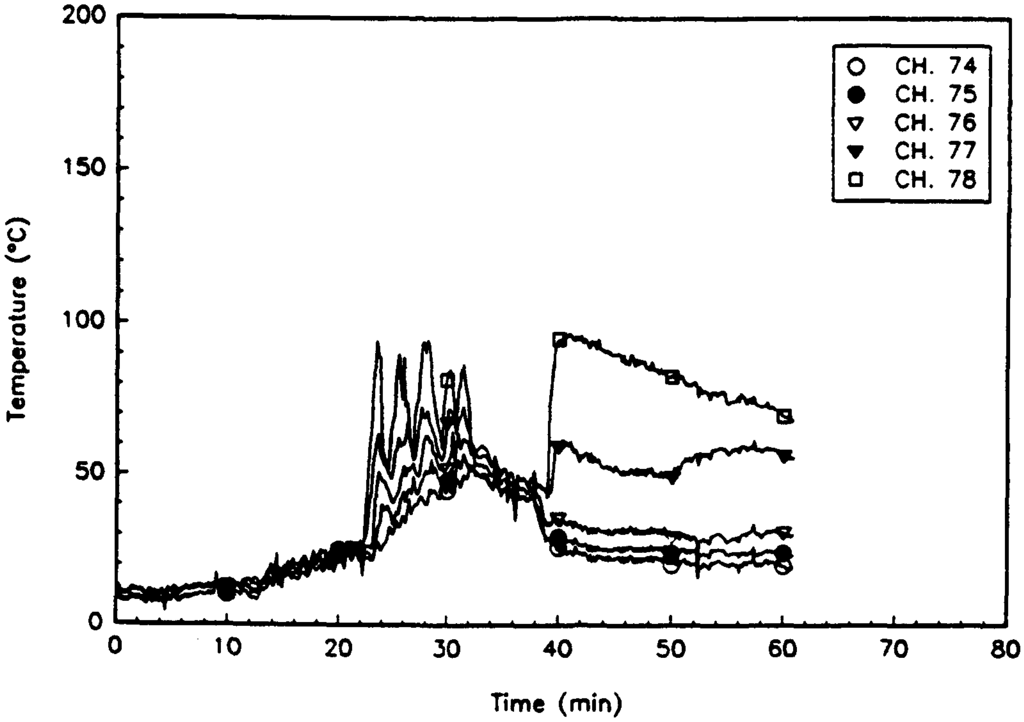

Fig. A34 – RICER 1 air temperatures aft, COL_4

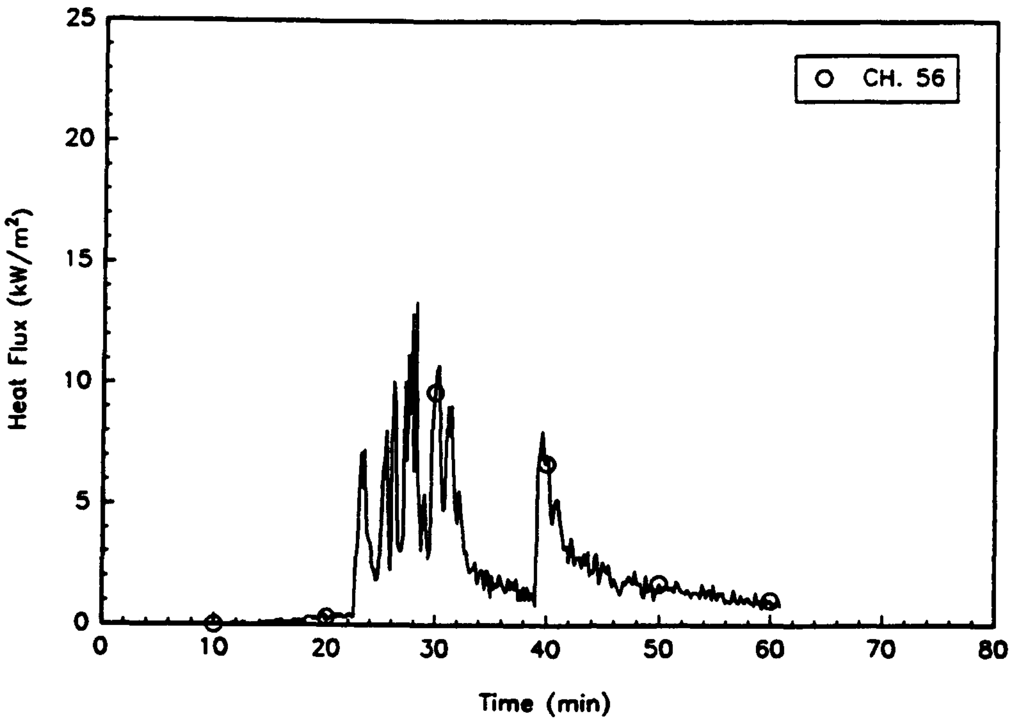

Fig. A35 – Total heat flux at RICER 1 overhead, COL_4

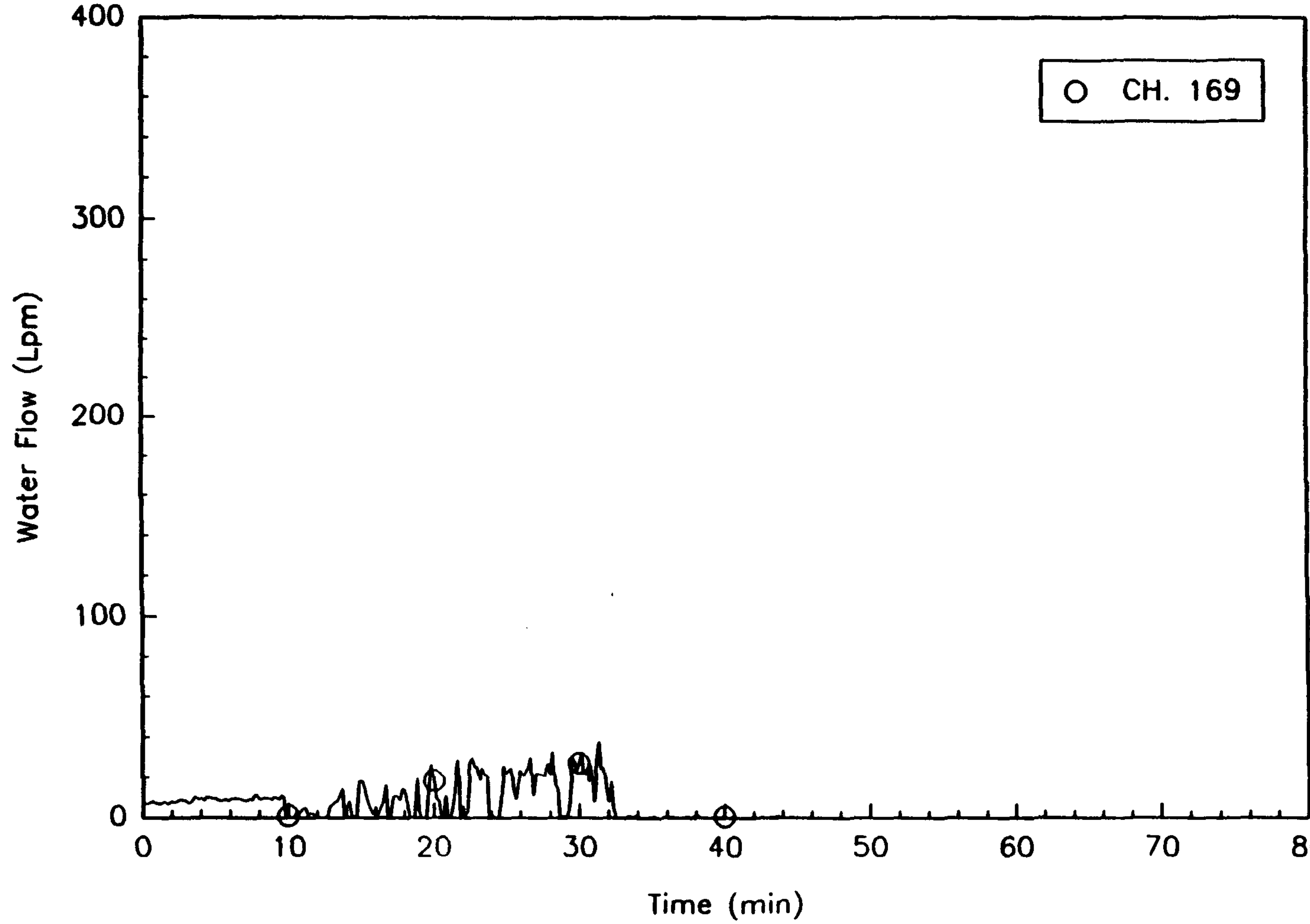

Fig. A36 — Water flow from cooling handline, COL_4

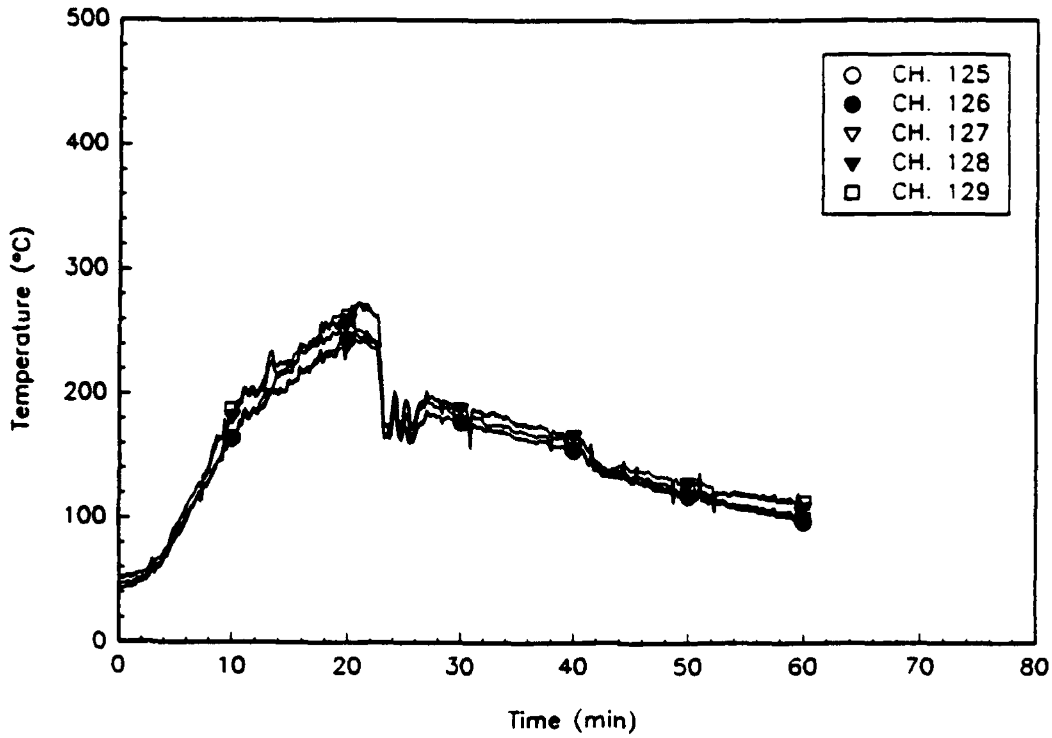

Fig. A37 — RICER 2 air temperatures forward, COL_5

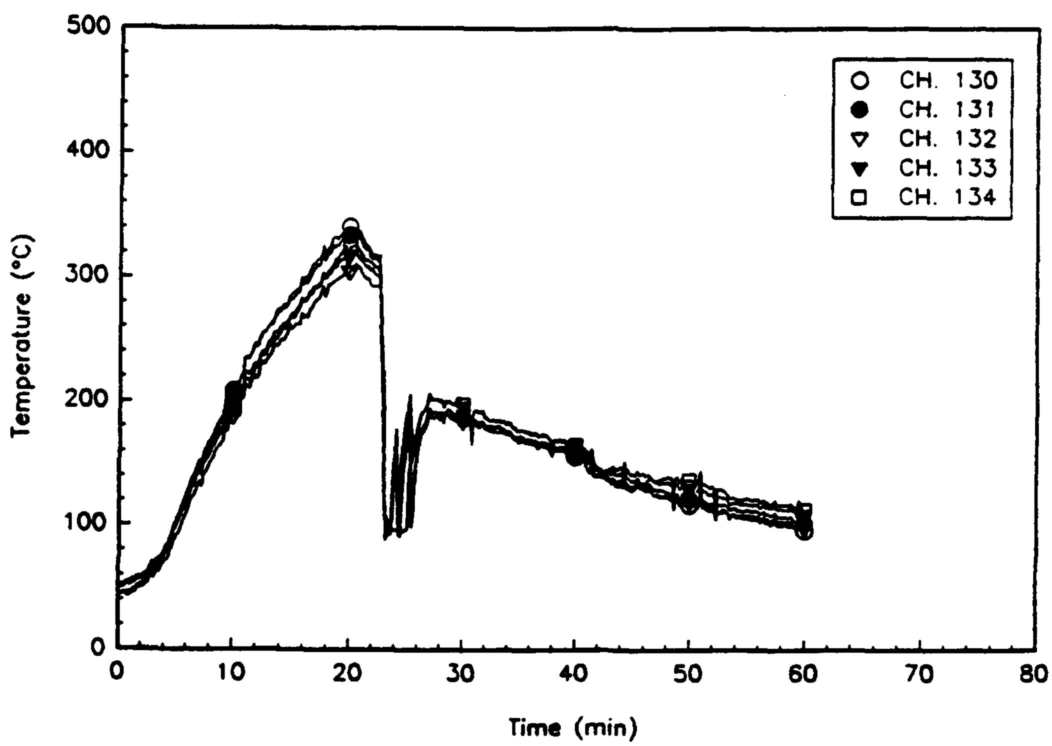

Fig. A38 — RICER 2 air temperatures aft, COL_5

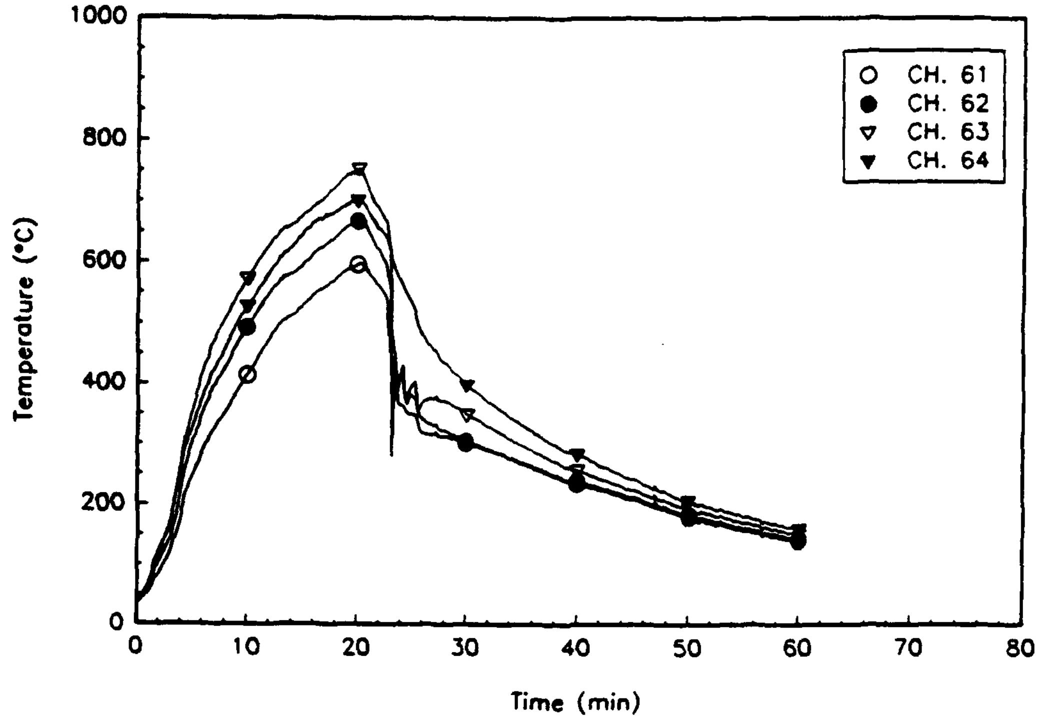

Fig. A39 — RICER 2 deck temperatures aft, COL_5

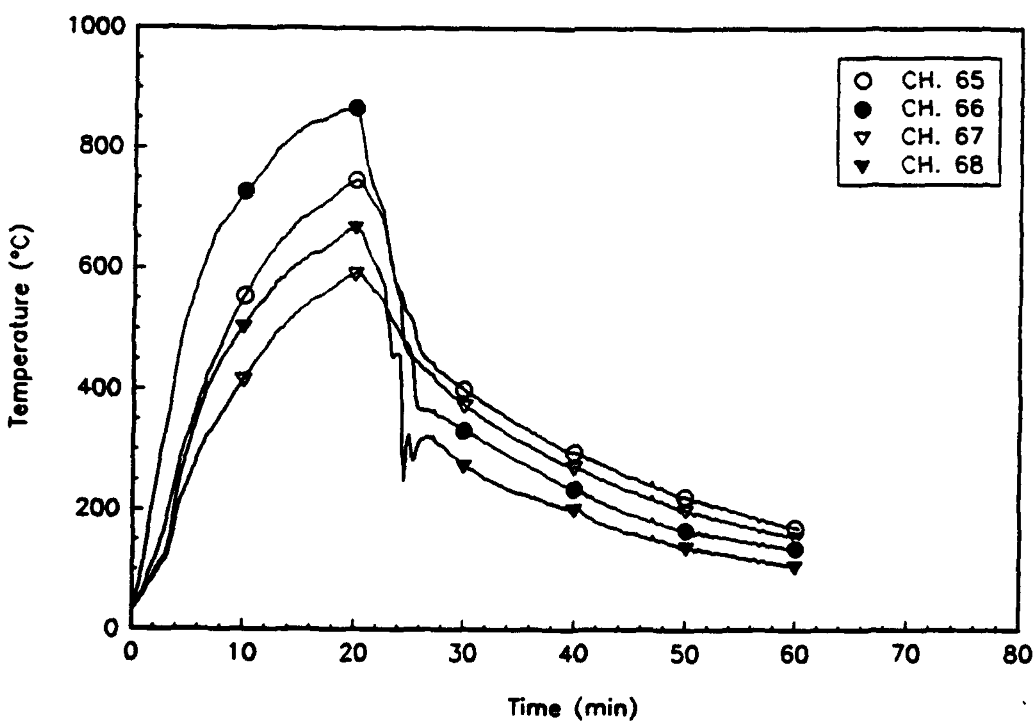

Fig. A40 — RICER 2 deck temperatures forward, COL_5

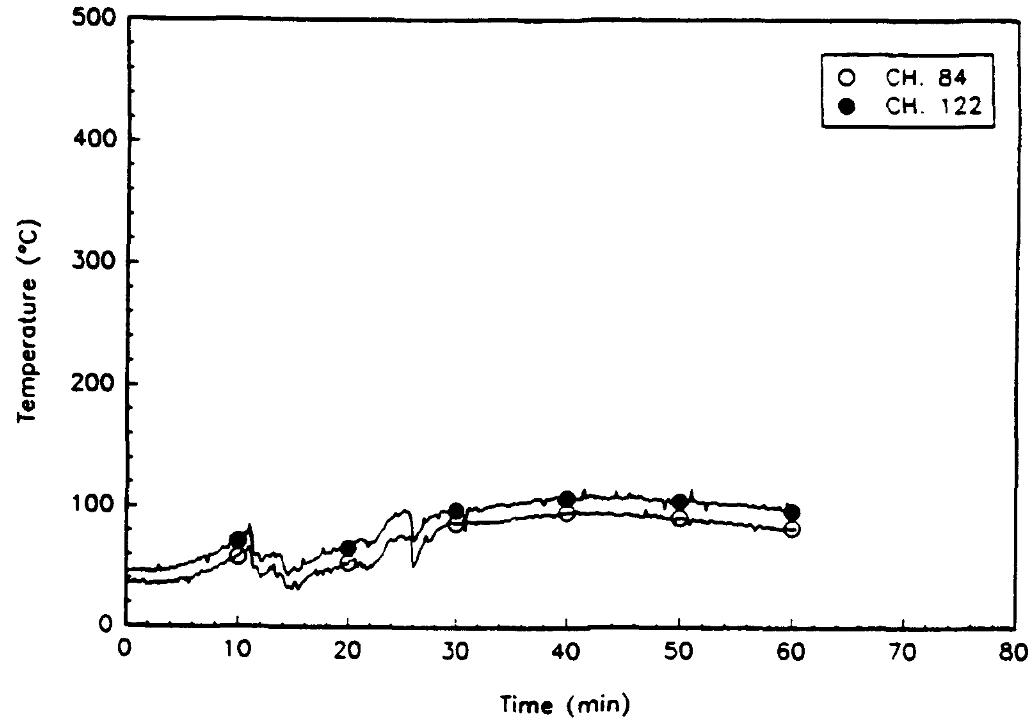

Fig. A41 – FR 81 bulkhead temperatures forward, COL_5

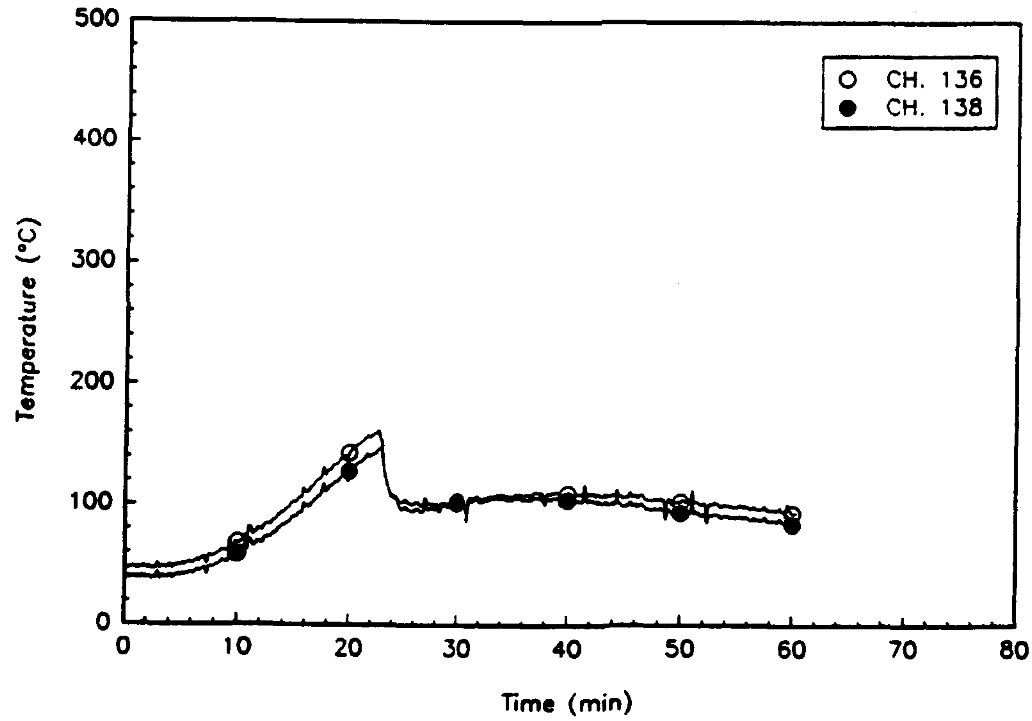

Fig. A42 – FR 88 bulkhead temperatures (RICER 2 side), COL_5

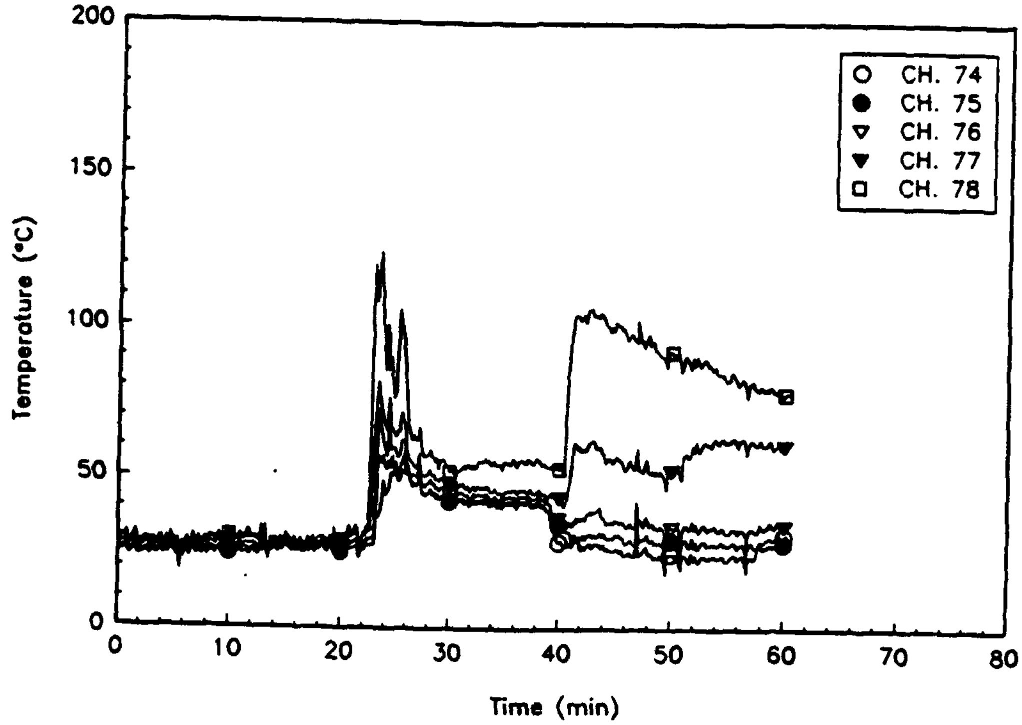

Fig. A43 – RICER 1 air temperatures aft, COL_5

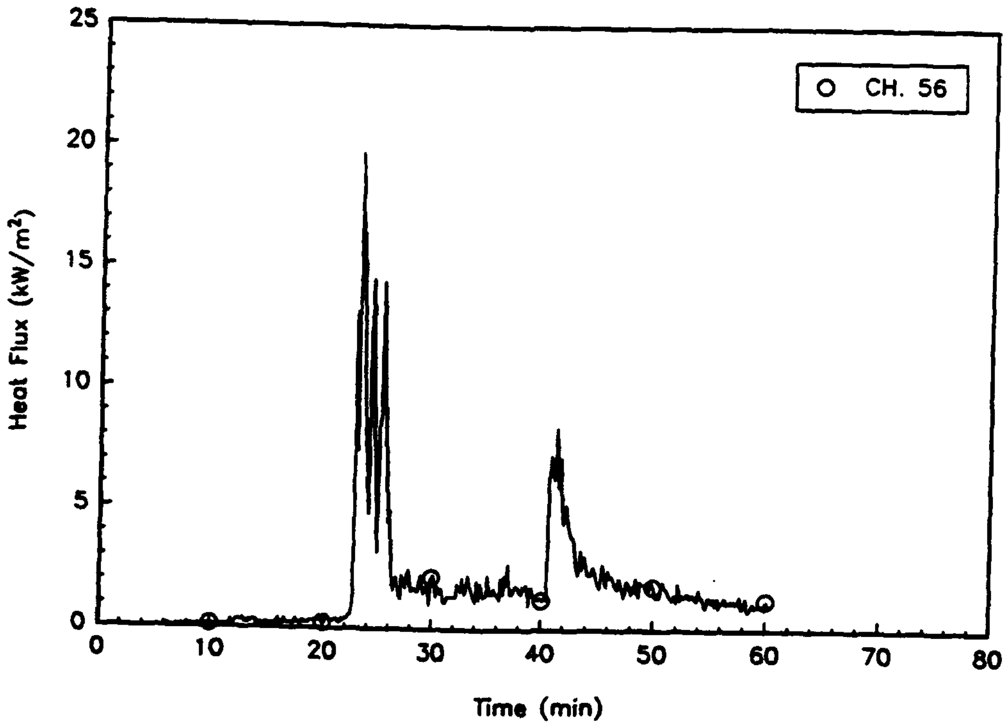

Fig. A44 – Total heat flux at RICER 1 overhead, COL_5

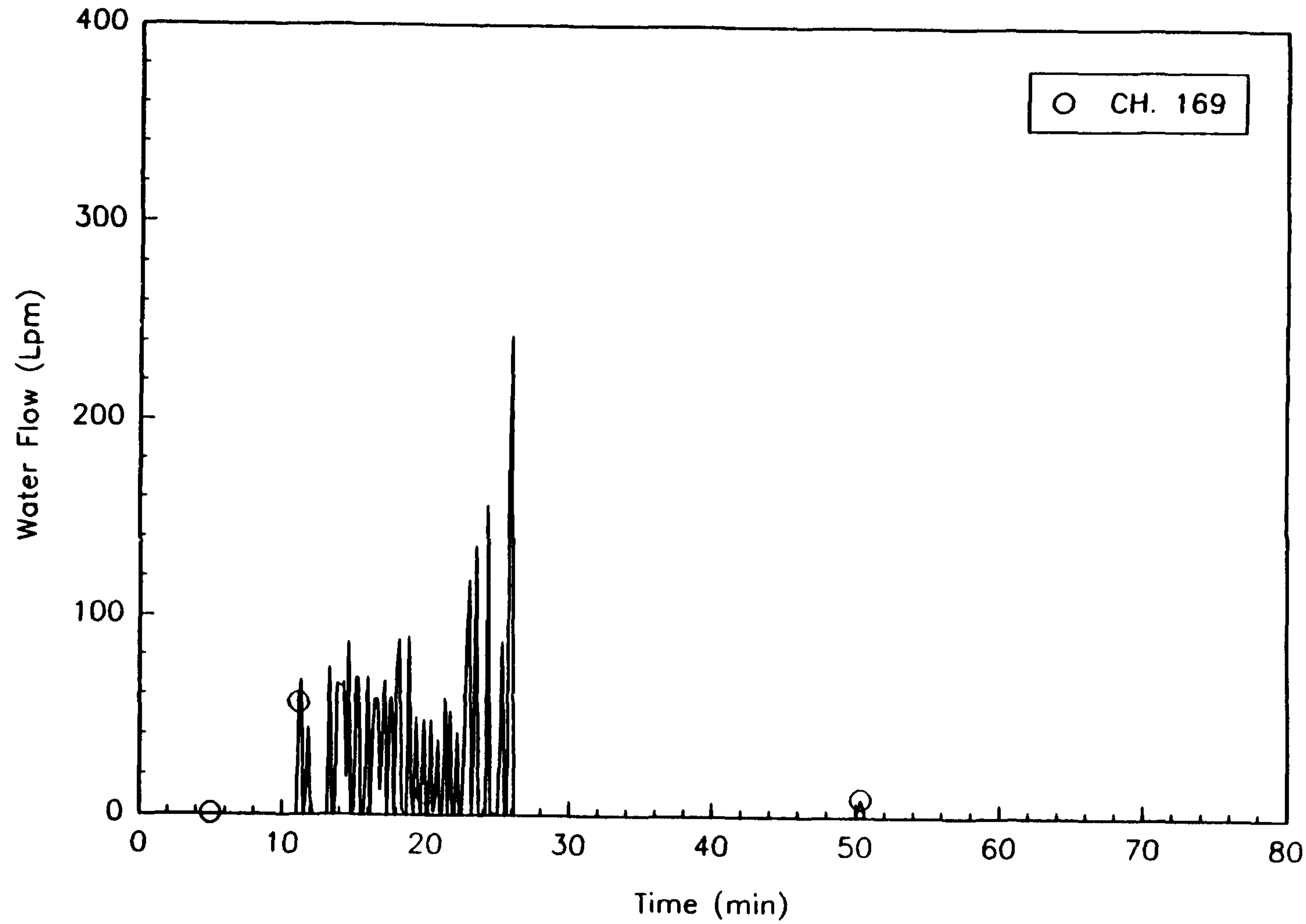

Fig. A45 — Water flow from cooling handline, COL_5

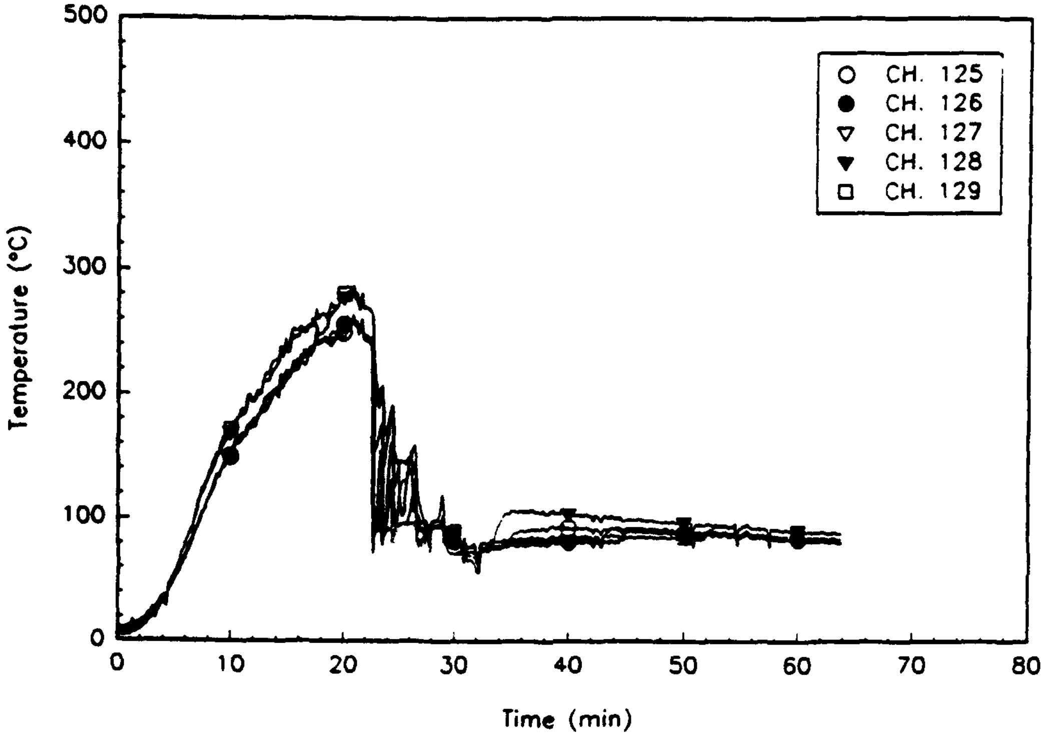

Fig. A46 – RICER 2 air temperatures forward, COL_6

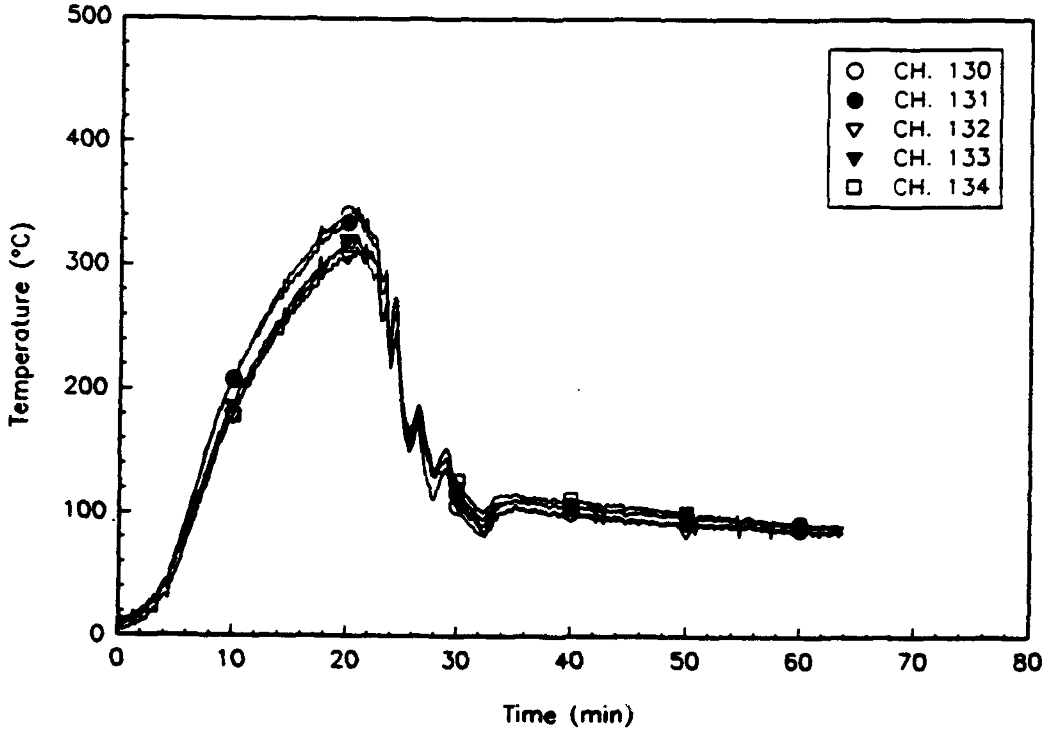

Fig. A47 – RICER 2 air temperatures aft, COL_6

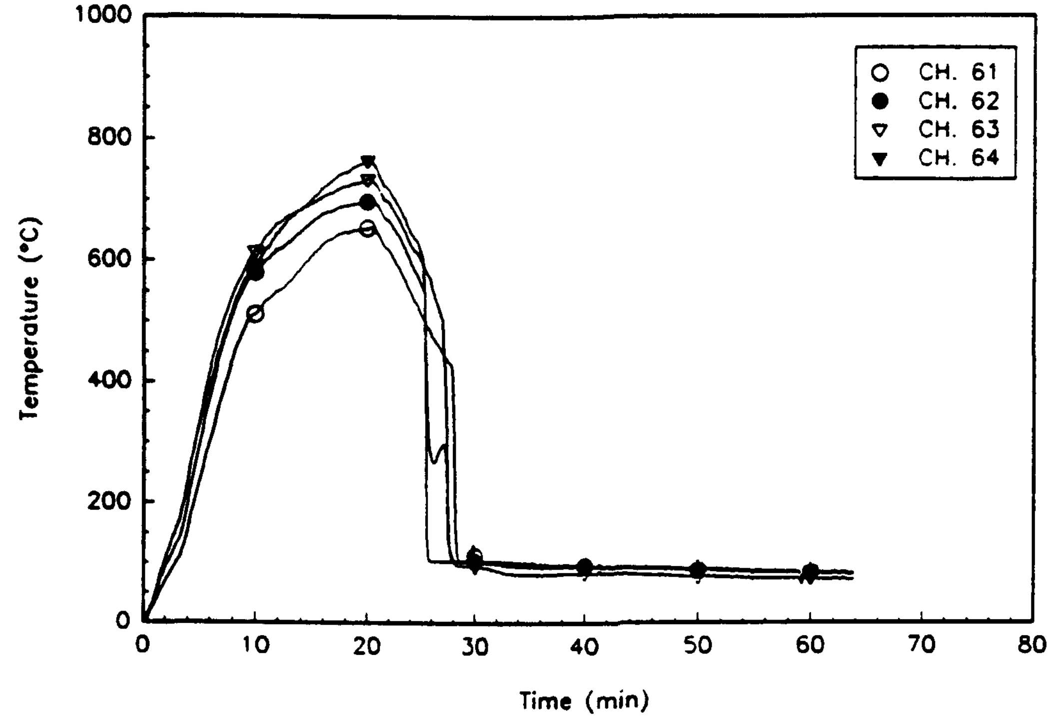

Fig. A48 – RICER 2 deck temperatures aft, COL_6

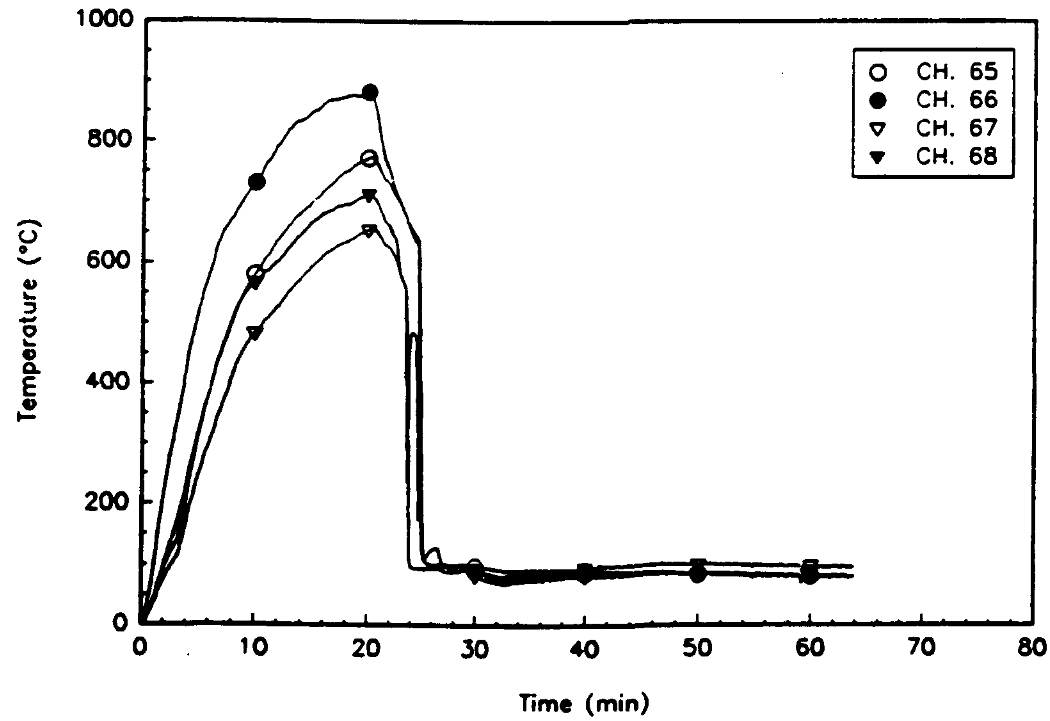

Fig. A49 – RICER 2 deck temperatures forward, COL_6

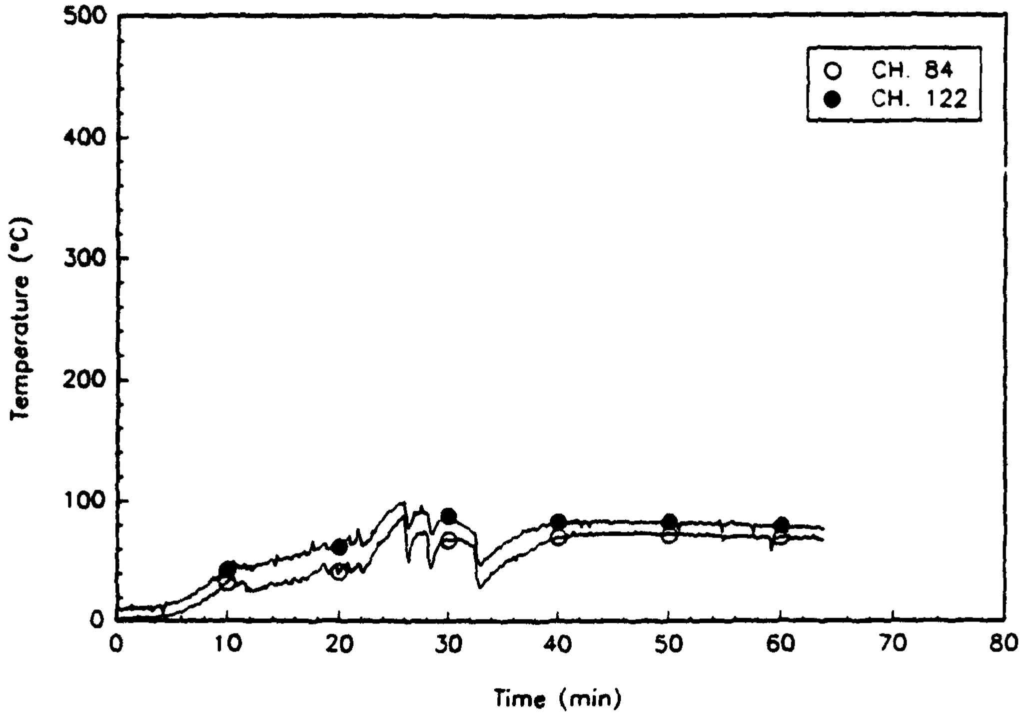

Fig. A50 — FR 81 bulkhead temperatures forward, COL_6

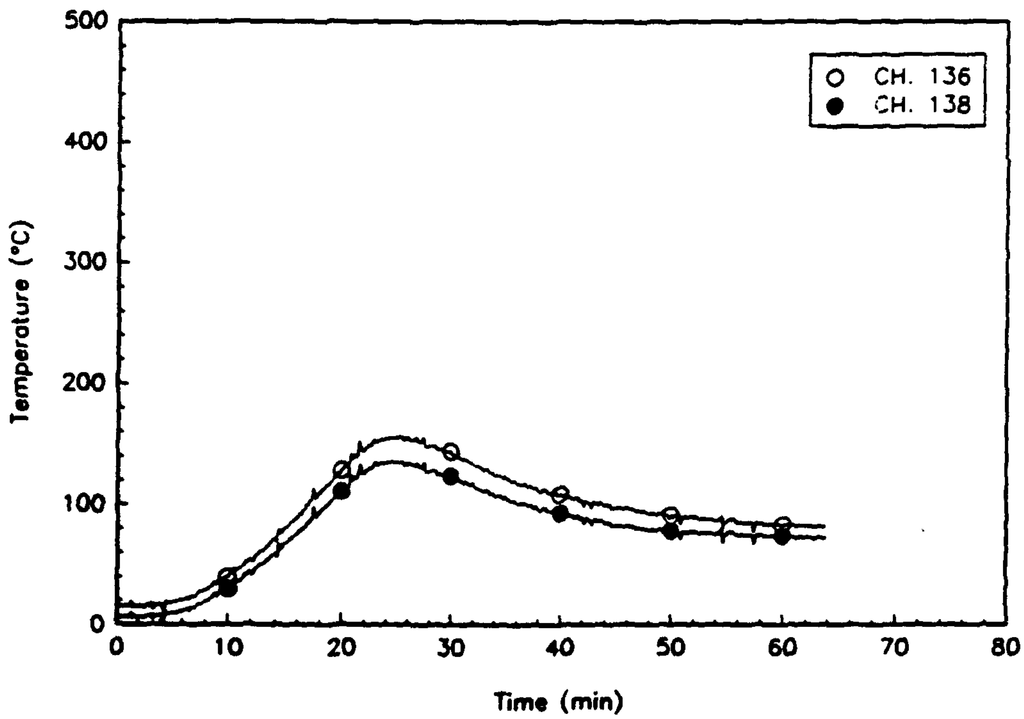

Fig. A51 — FR 88 bulkhead temperatures (RICER 2 side), COL_6

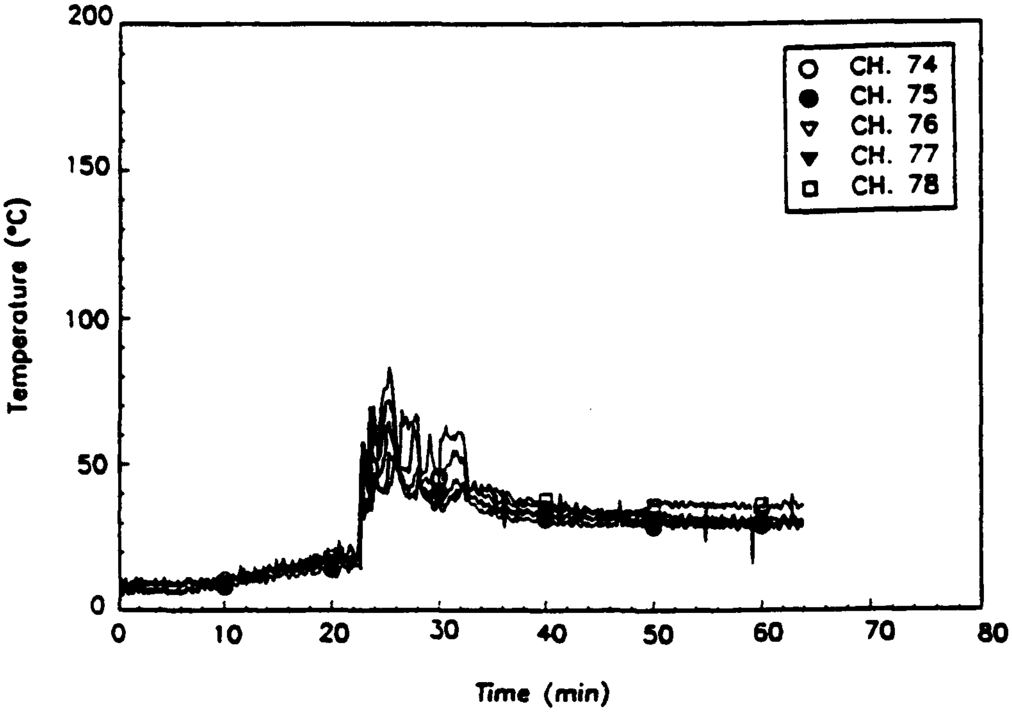

Fig. A52 — RICER 1 air temperatures aft, COL_6

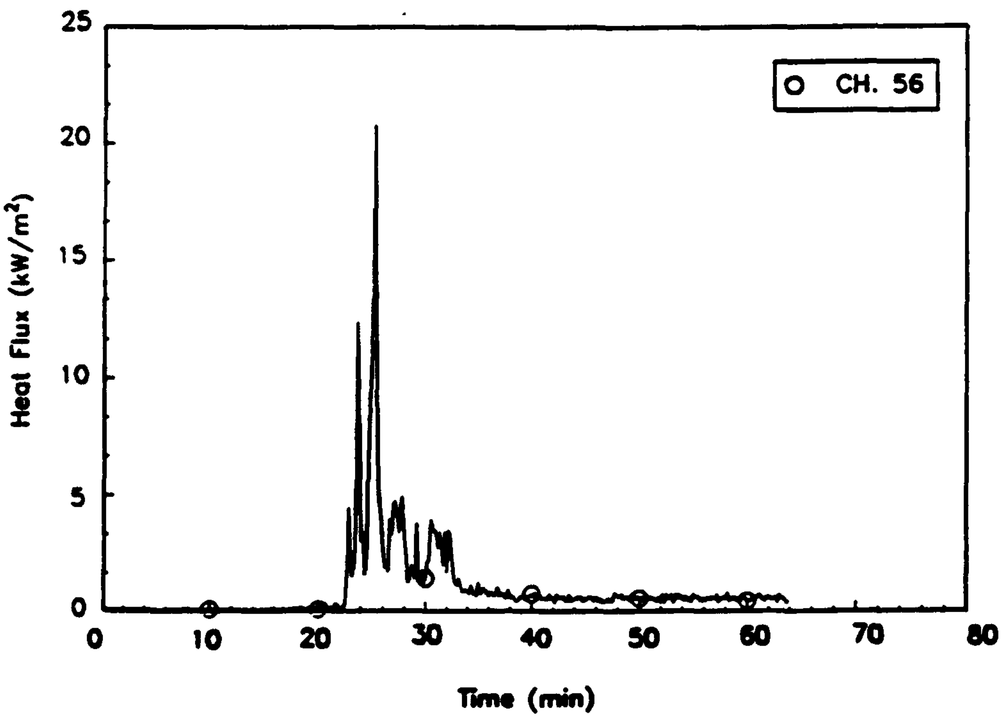

Fig. A53 — Total heat flux at RICER 1 overhead, COL_6

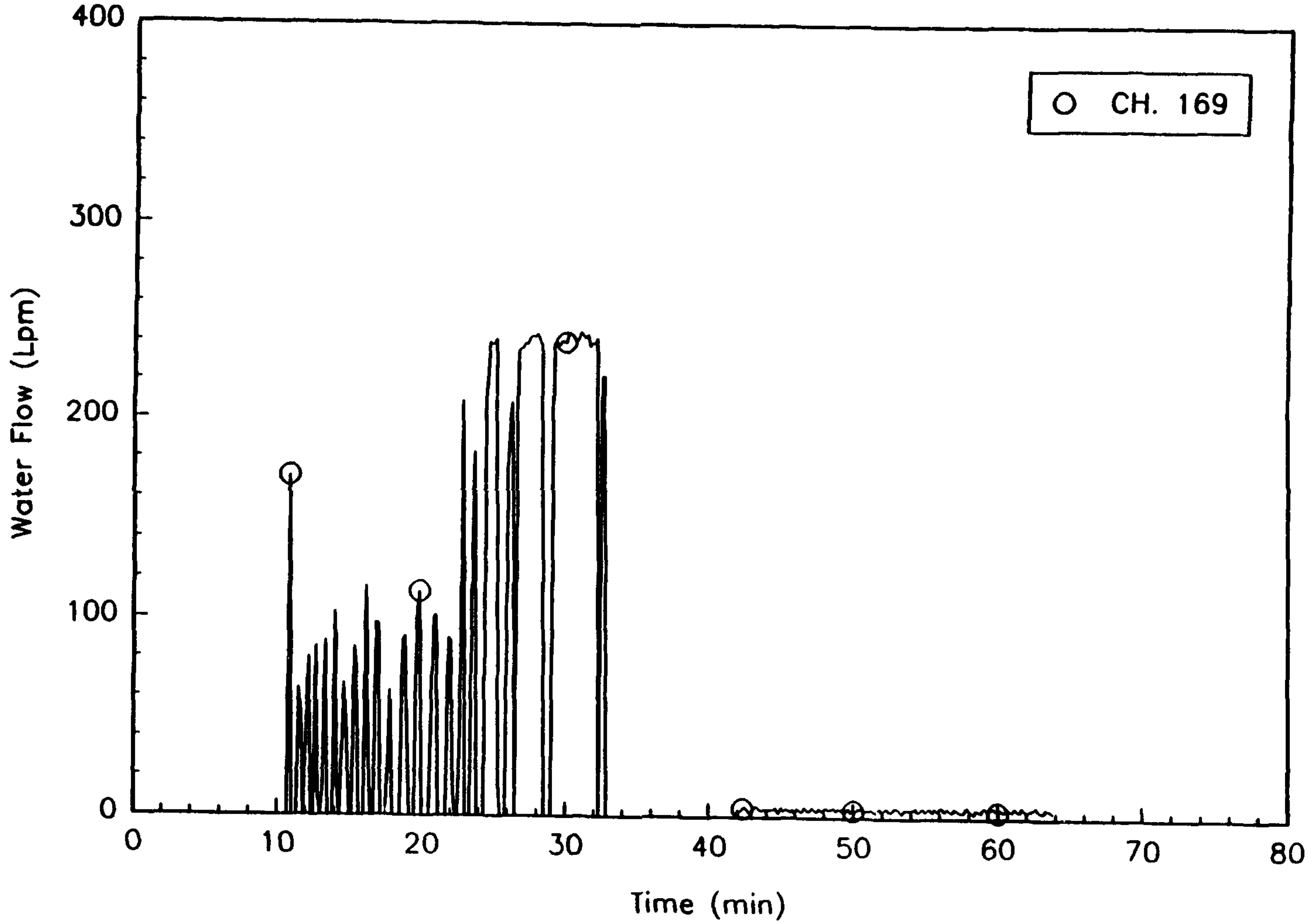

Fig. A54 — Water flow from cooling handline, COL_6

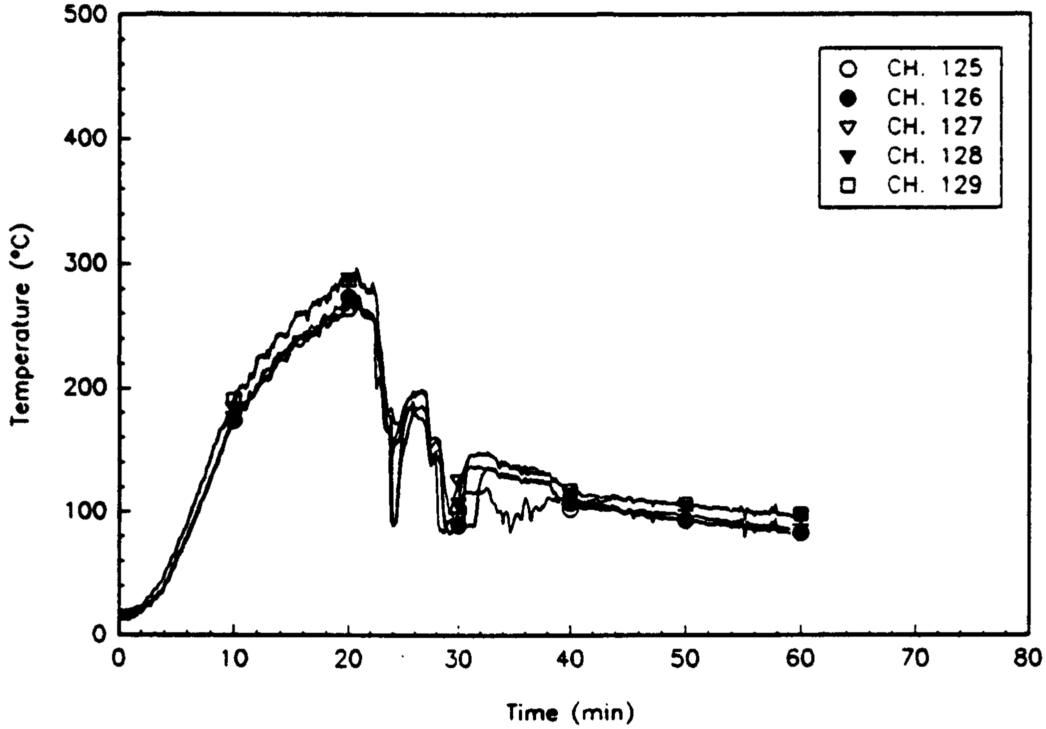

Fig. A55 – RICER 2 air temperatures forward, COL_7

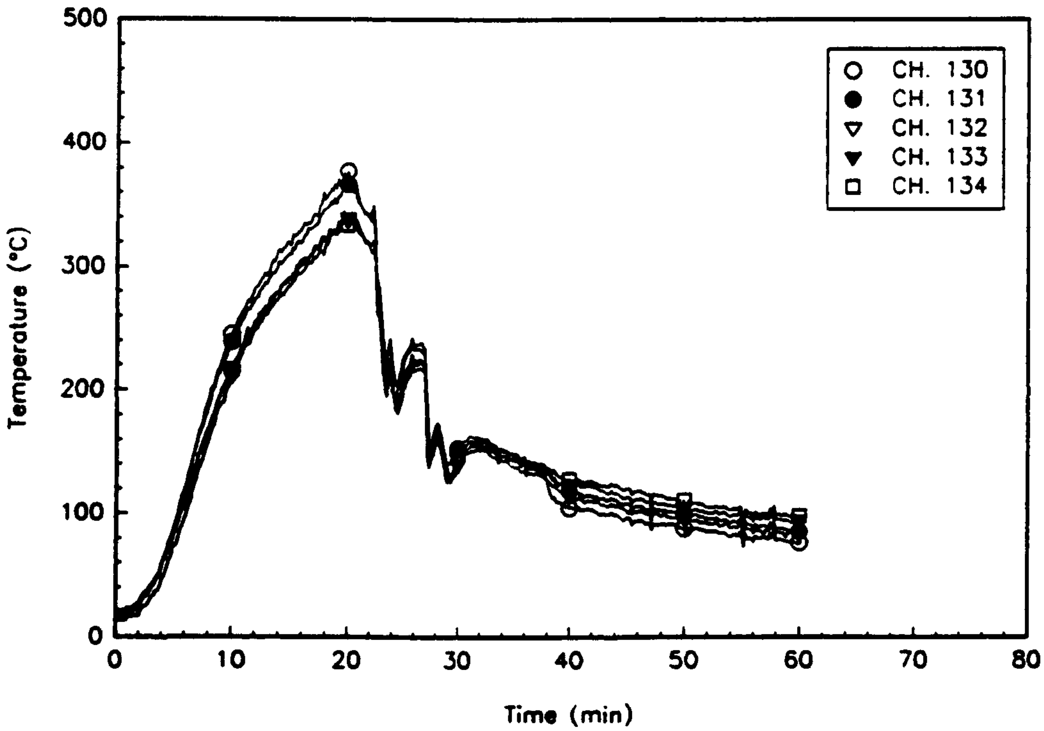

Fig. A56 – RICER 2 air temperatures aft, COL_7

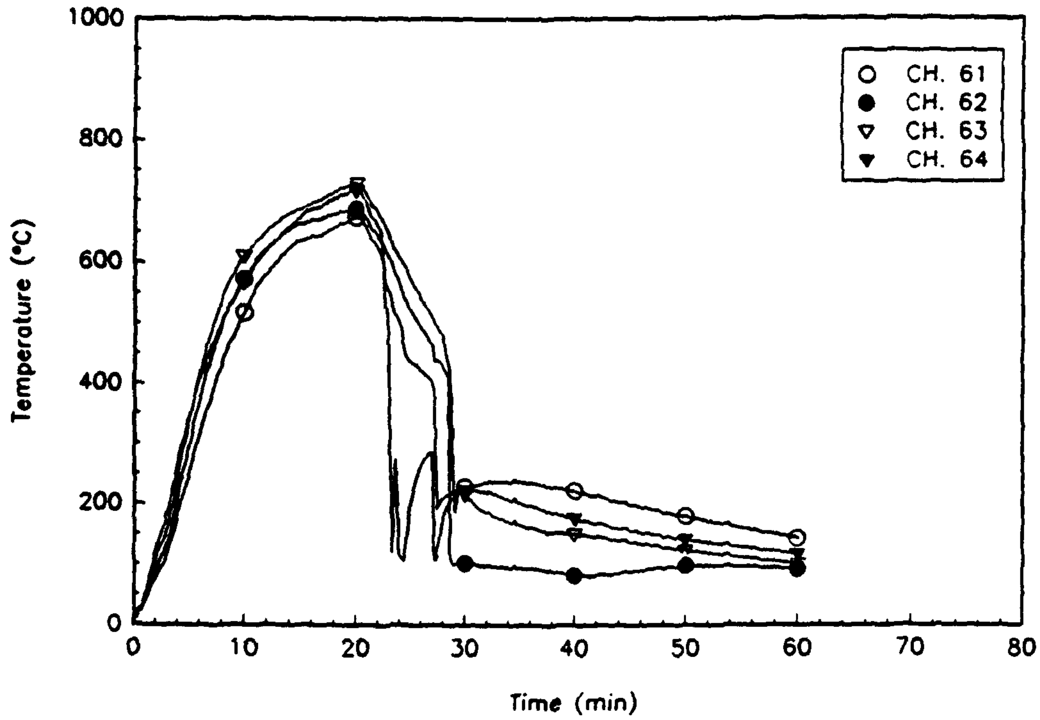

Fig. A57 — RICER 2 deck temperatures aft, COL_7

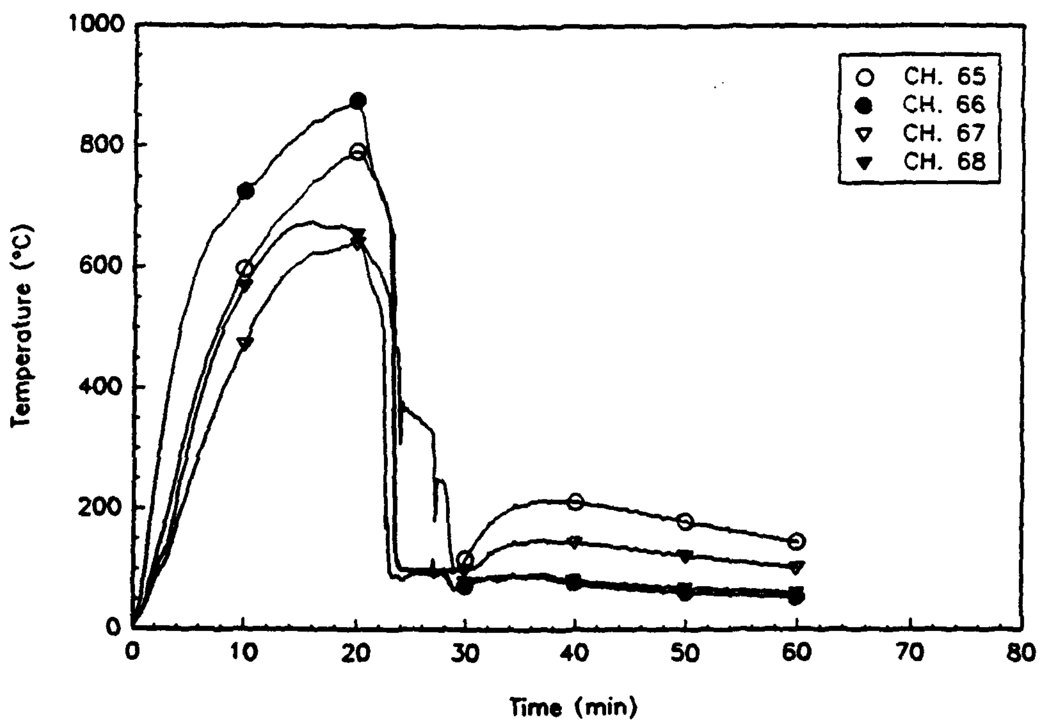

Fig. A58 — RICER 2 deck temperatures forward, COL_7

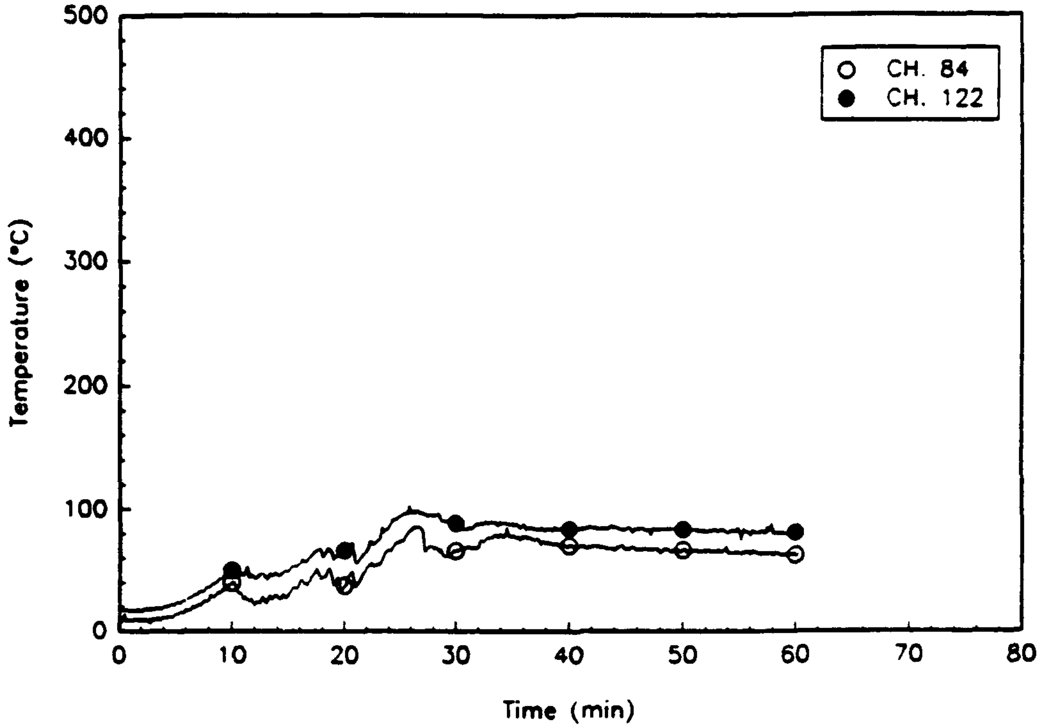

Fig. A59 — FR 81 bulkhead temperatures forward, COL_7

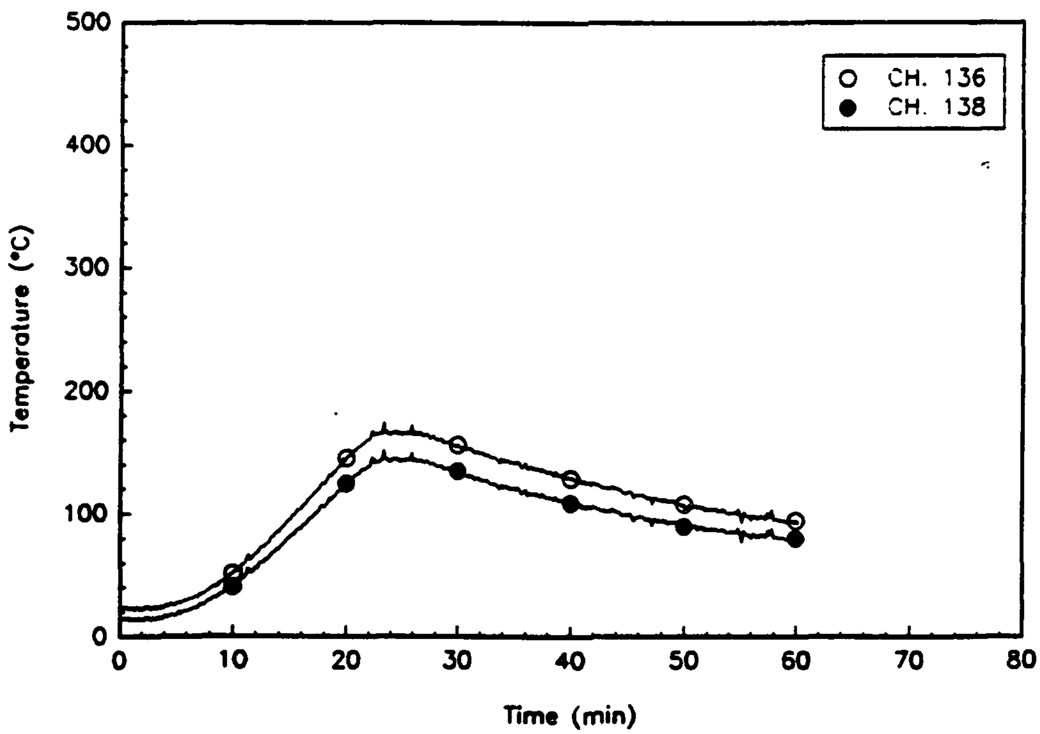

Fig. A60 — FR 88 bulkhead temperatures (RICER 2 side), COL_7

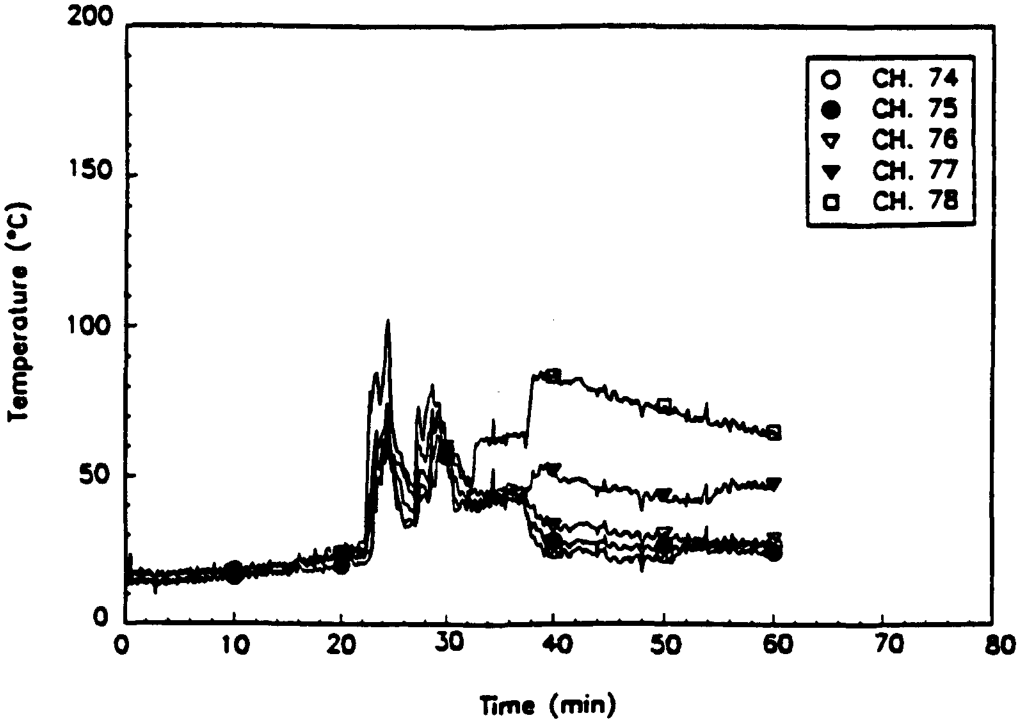

Fig. A61 – RICER 1 air temperatures aft, COL_7

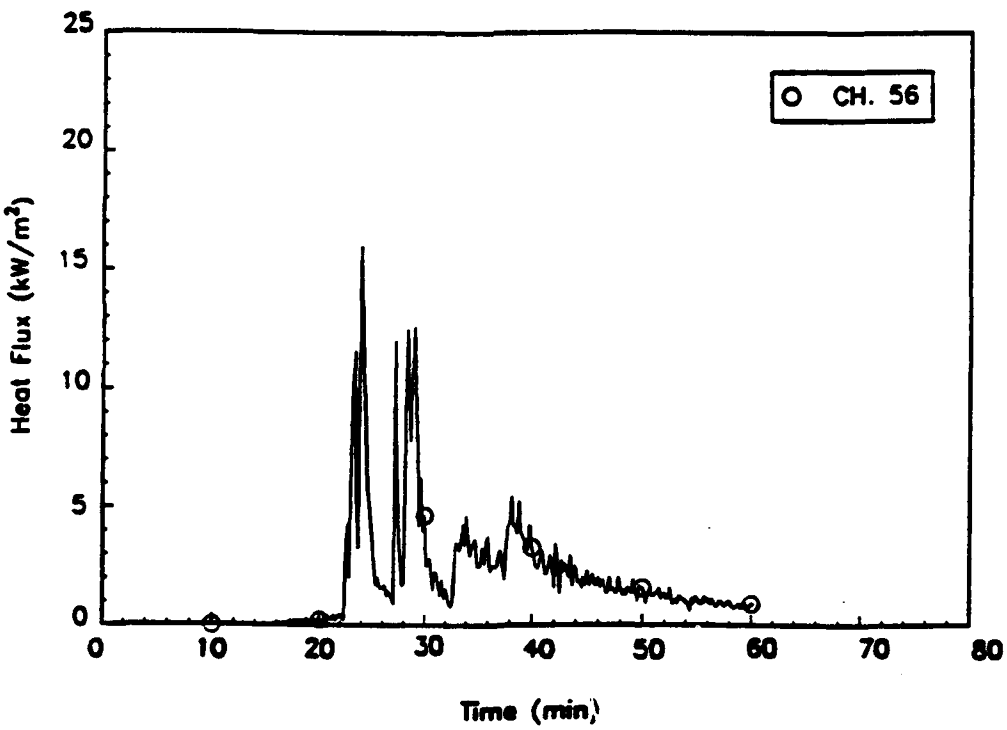

Fig. A62 – Total heat flux at RICER 1 overhead, COL_7

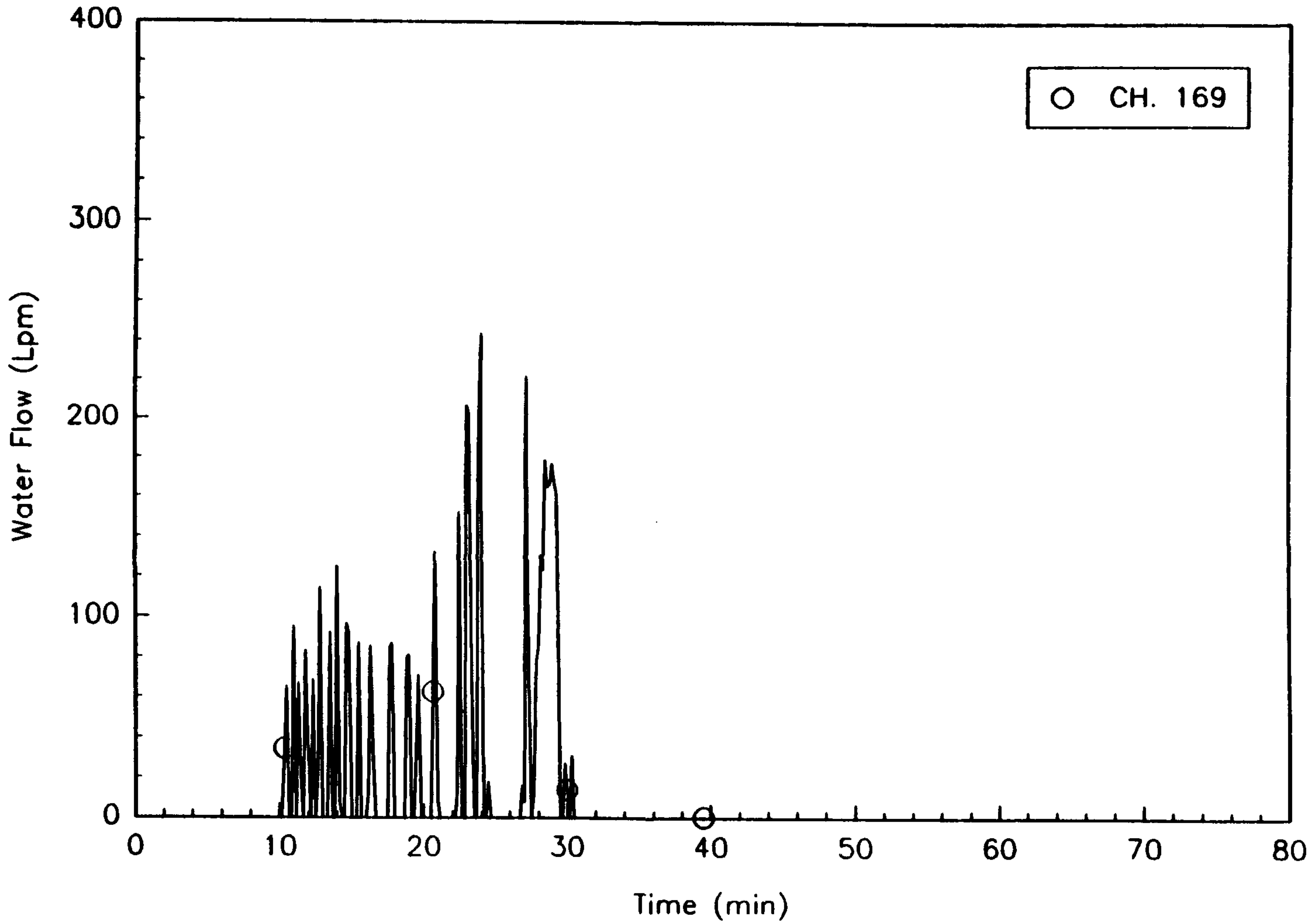

Fig. A63 — Water flow from cooling handline, COL_7

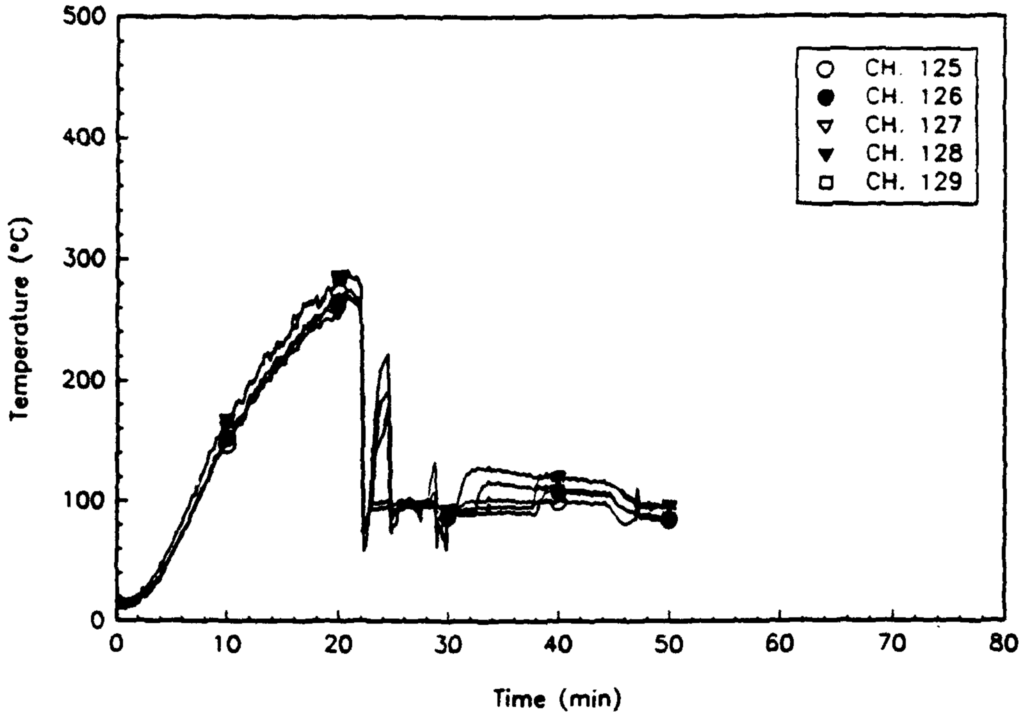

Fig. A64 — RICER 2 air temperatures forward, COL_8

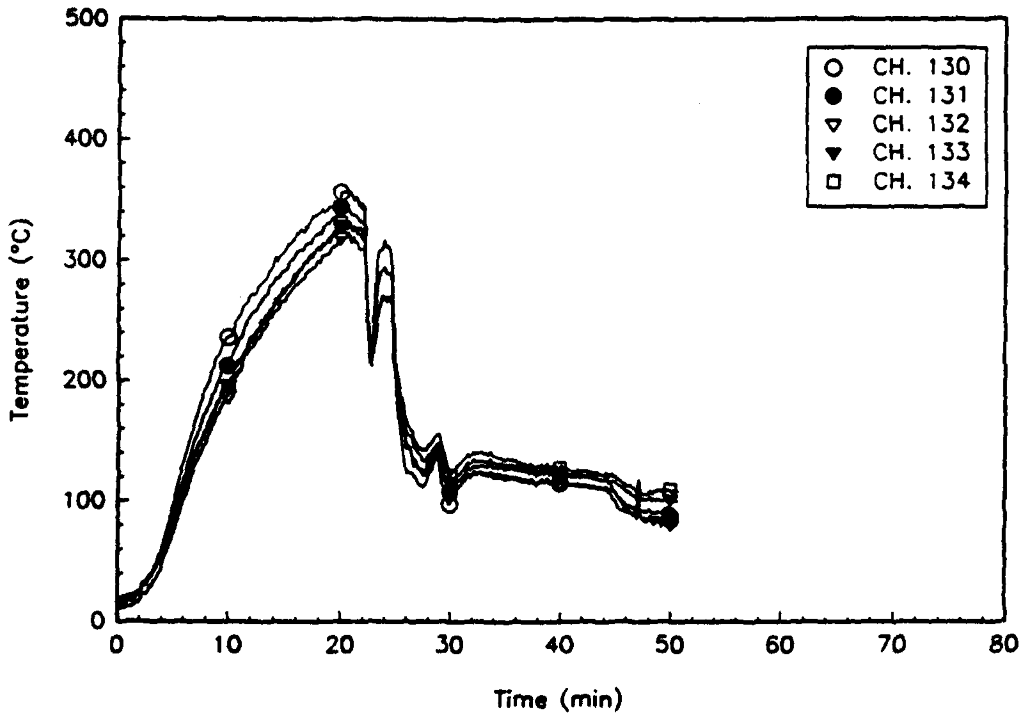

Fig. A65 — RICER 2 air temperatures aft, COL_8

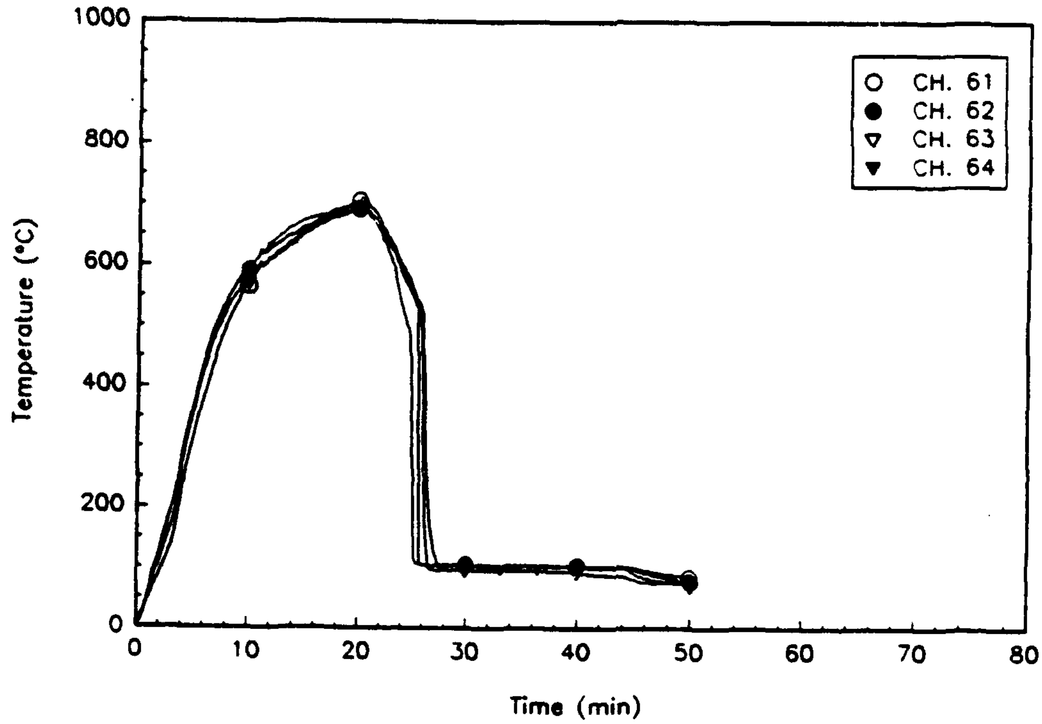

Fig. A66 – RICER 2 deck temperatures aft, COL_8

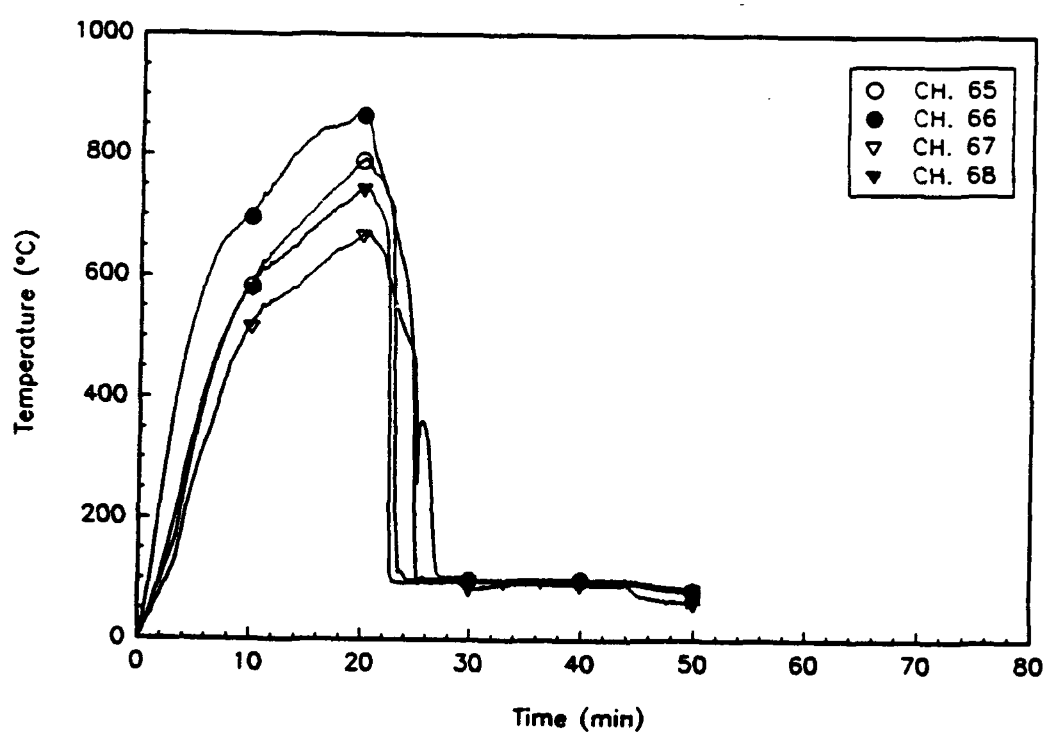

Fig. A67 – RICER 2 deck temperatures forward, COL_8

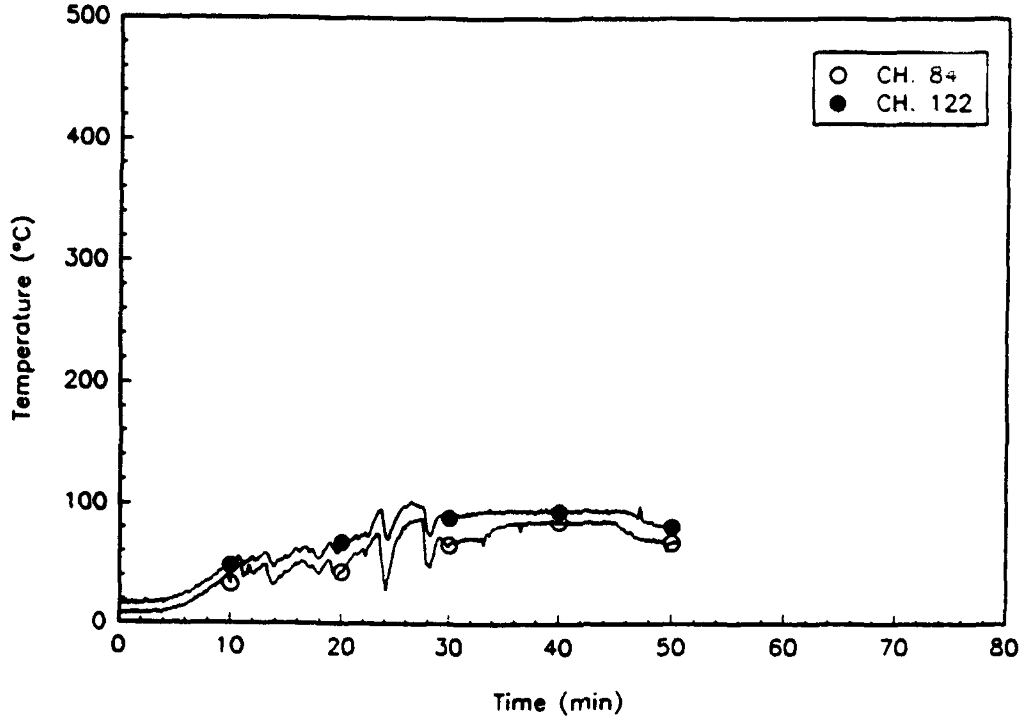

Fig. A68 — FR 81 bulkhead temperatures forward, COL_8

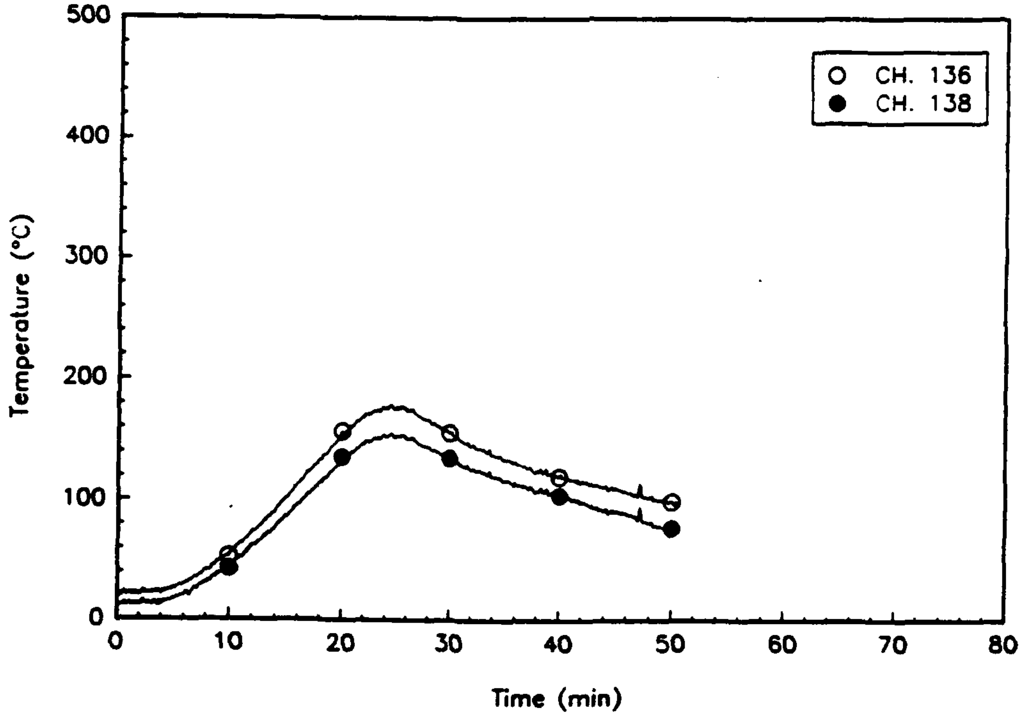

Fig A69 — FR 88 bulkhead temperatures (RICER 2 side), COL_8

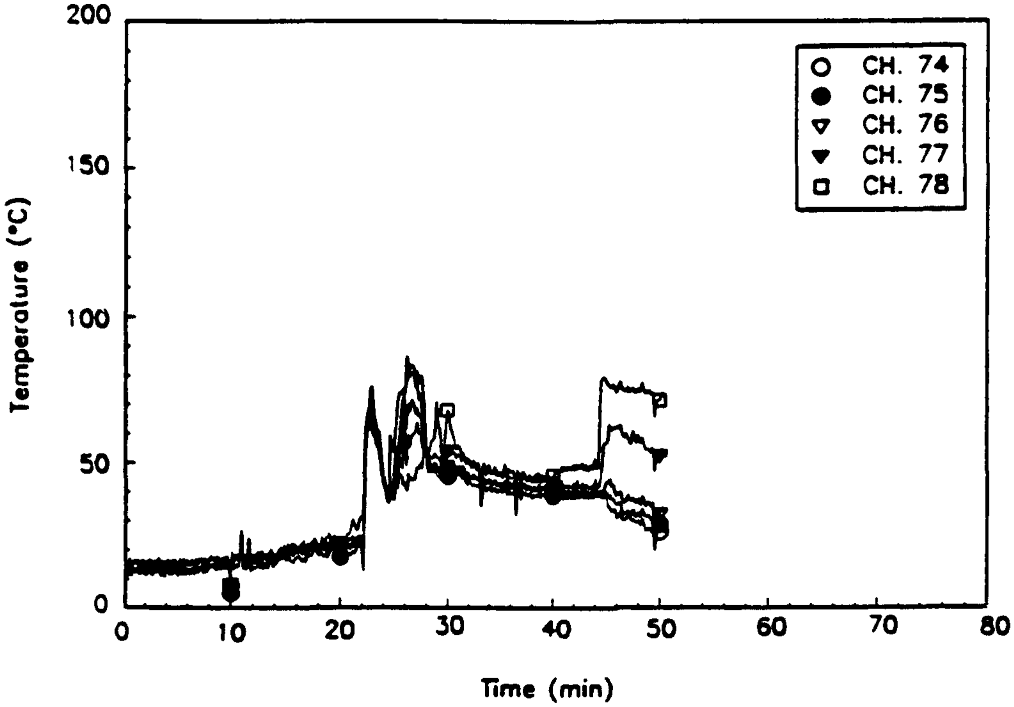

Fig. A70 – RICER 1 air temperatures aft, COL_8

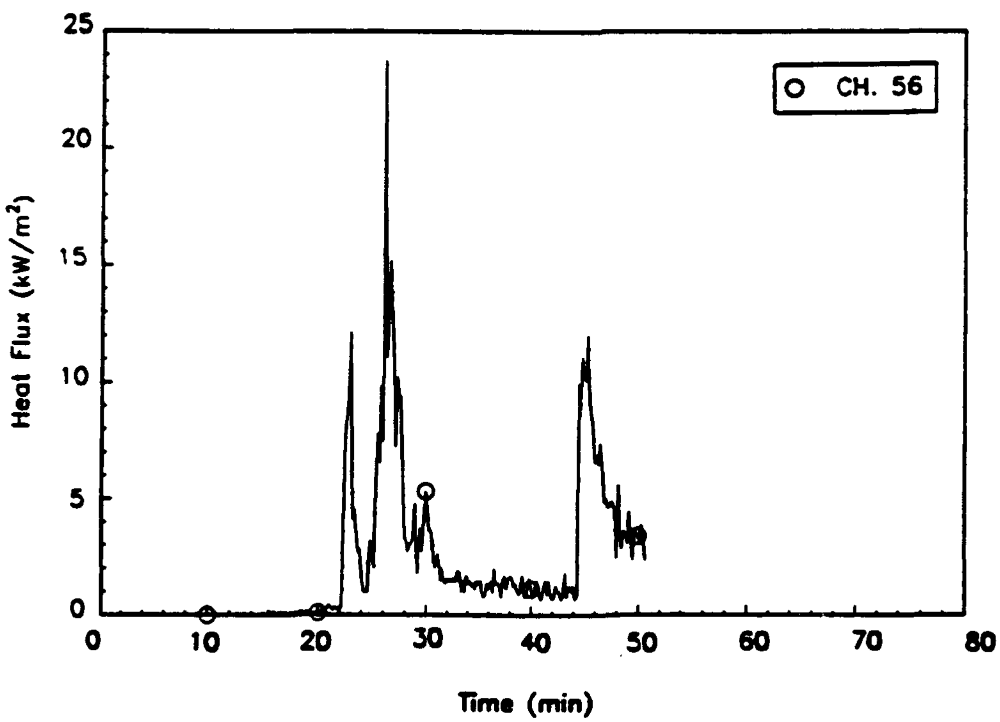

Fig. A71 – Total heat flux at RICER 1 overhead, COL_8

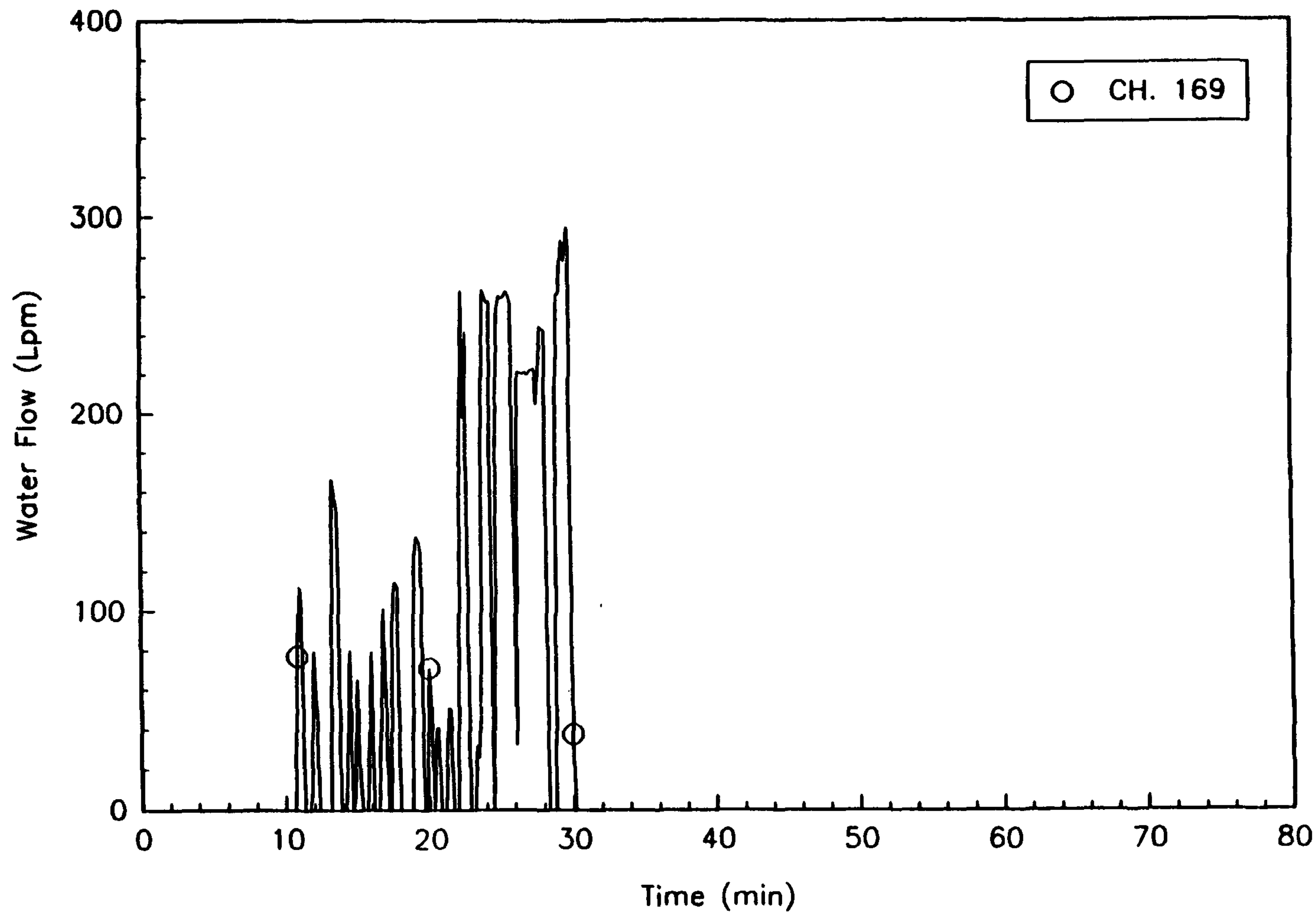

Fig. A72 — Water flow from cooling handline, COL_8

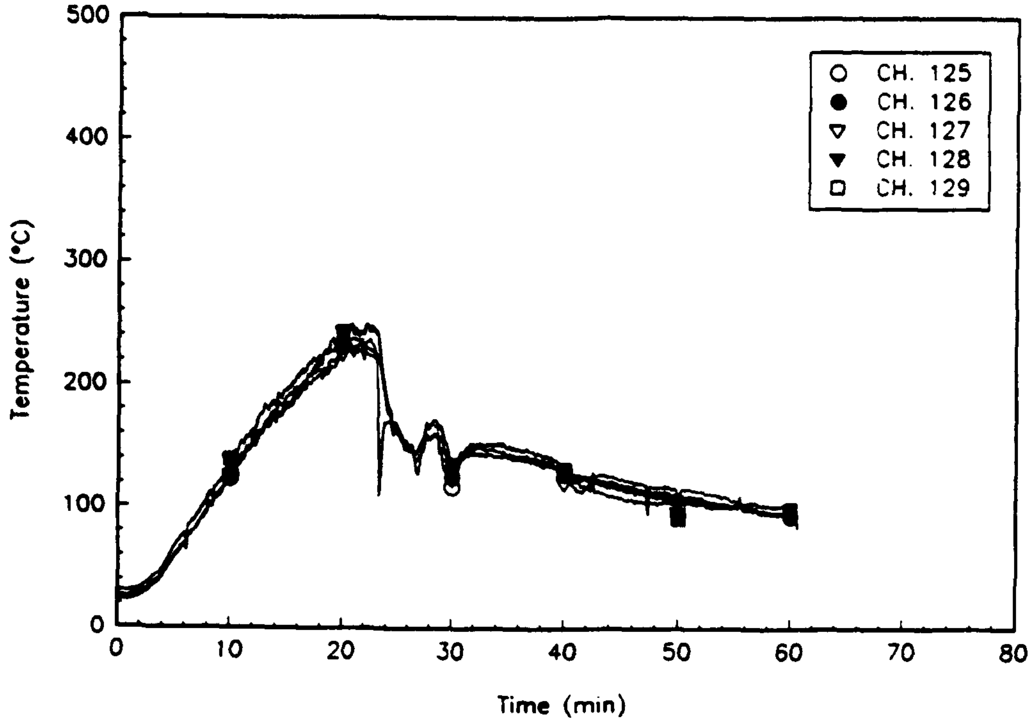

Fig. A73 — RICER 2 air temperatures forward, COL_9

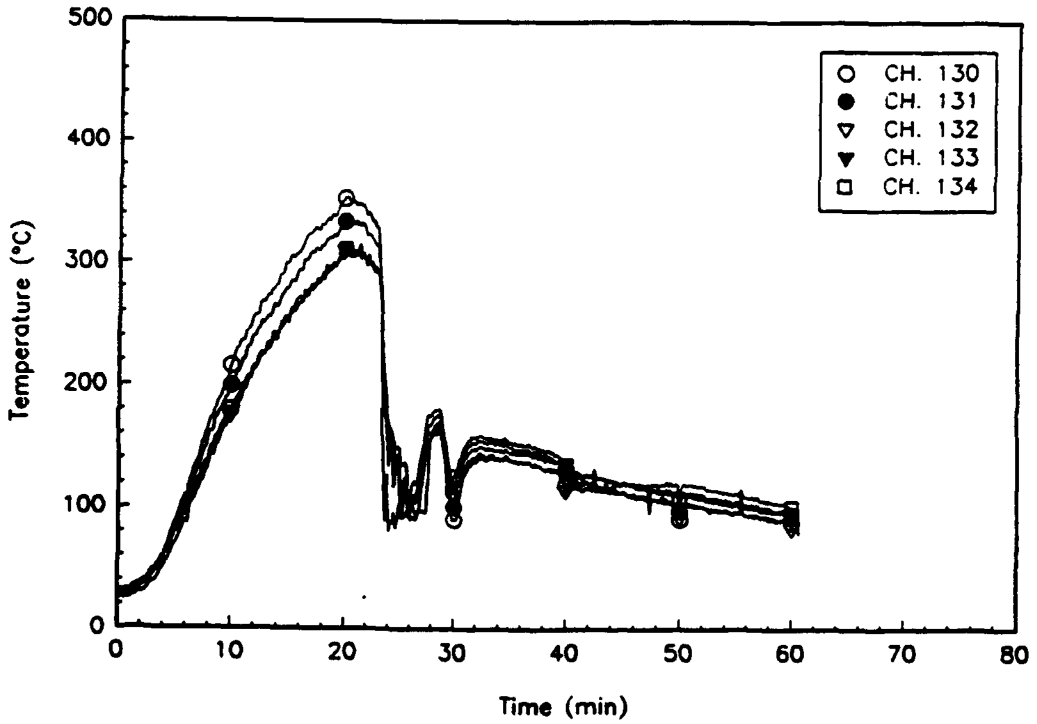

Fig. A74 — RICER 2 air temperatures aft, COL_9

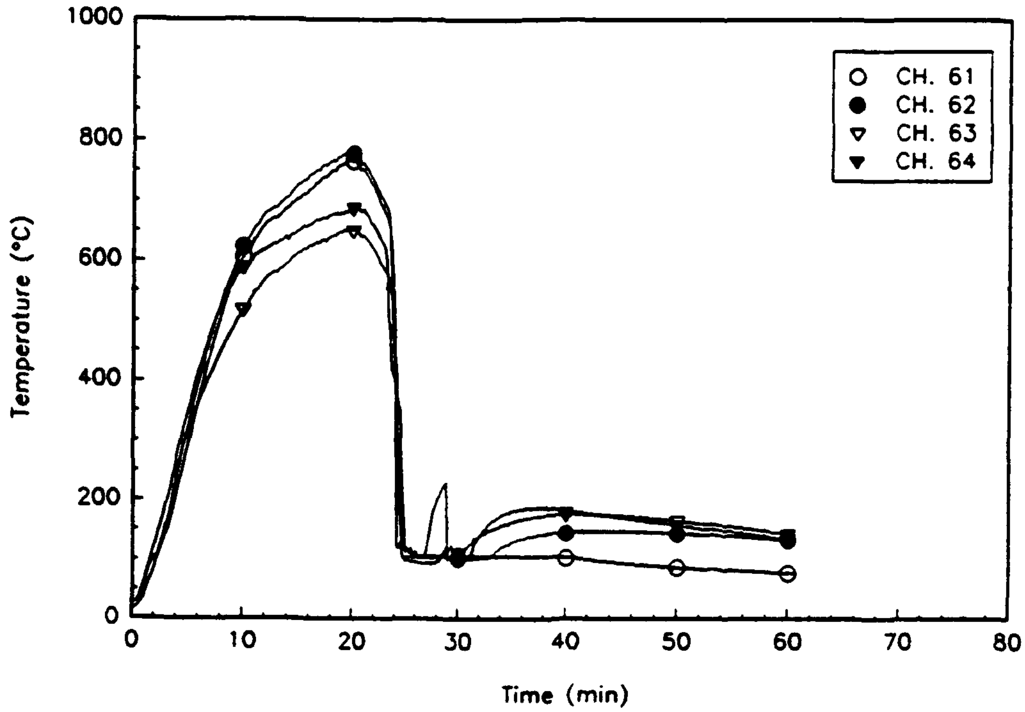

Fig. A75 — RICER 2 deck temperatures aft, COL_9

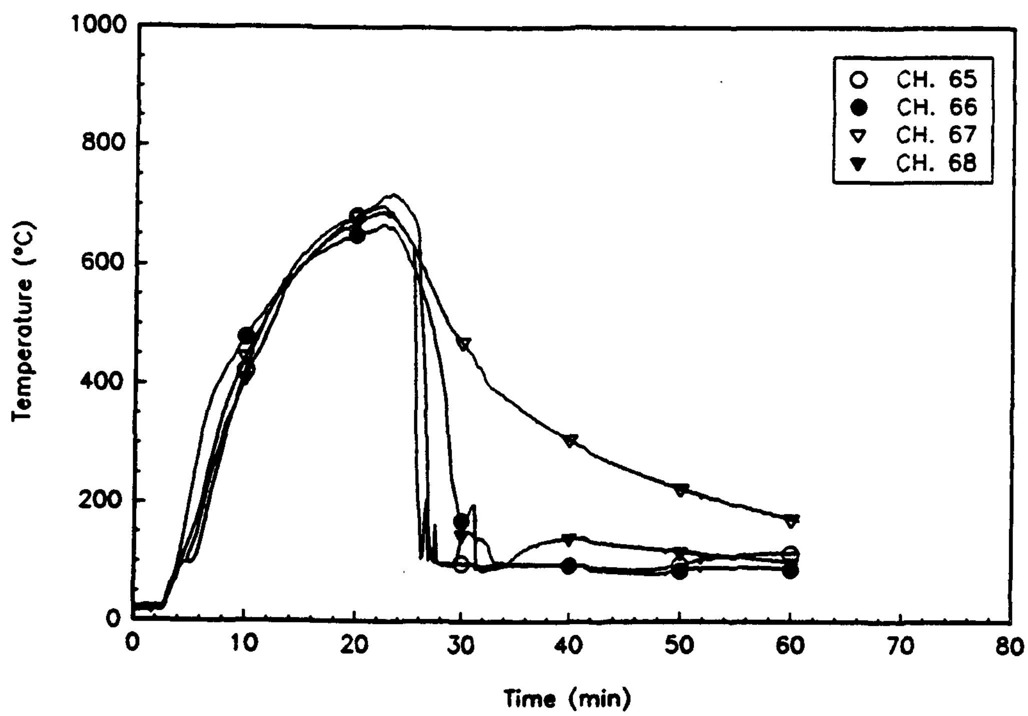

Fig. A76 — RICER 2 deck temperatures forward, COL_9

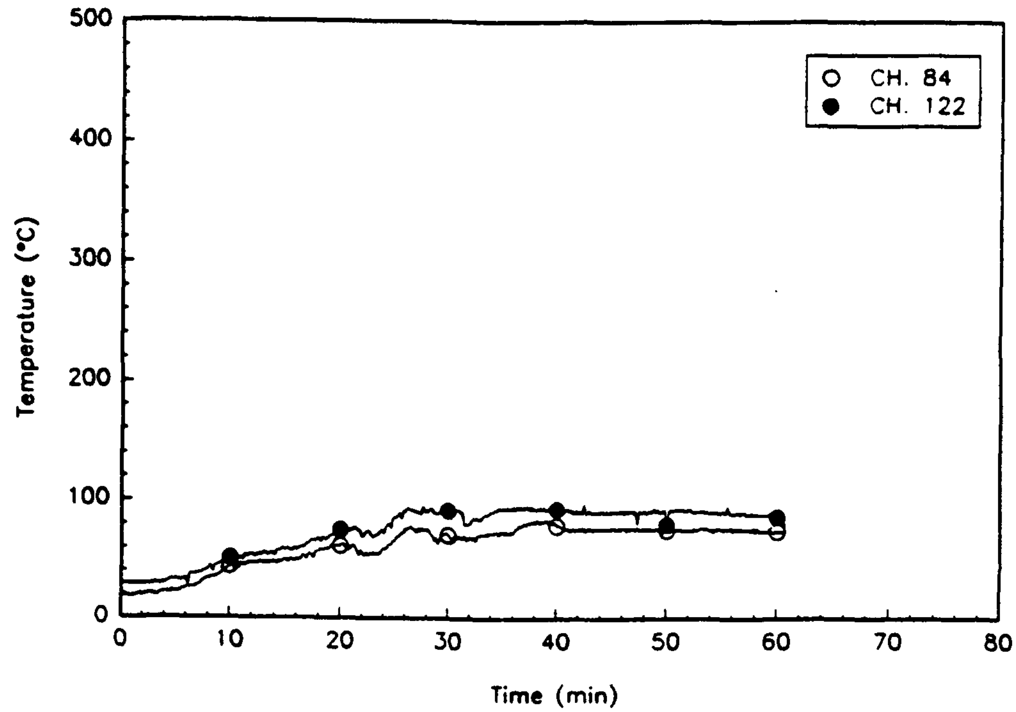

Fig. A77 – FR 81 bulkhead temperatures forward, COL_9

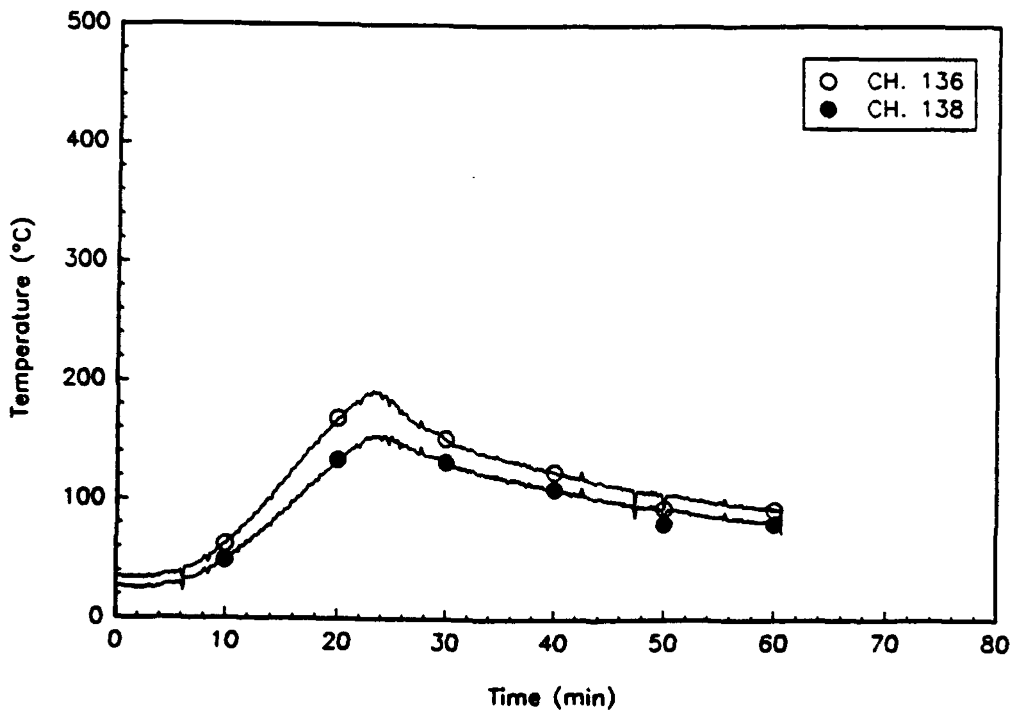

Fig. A78 – FR 88 bulkhead temperatures
(RICER 2 side), COL_9

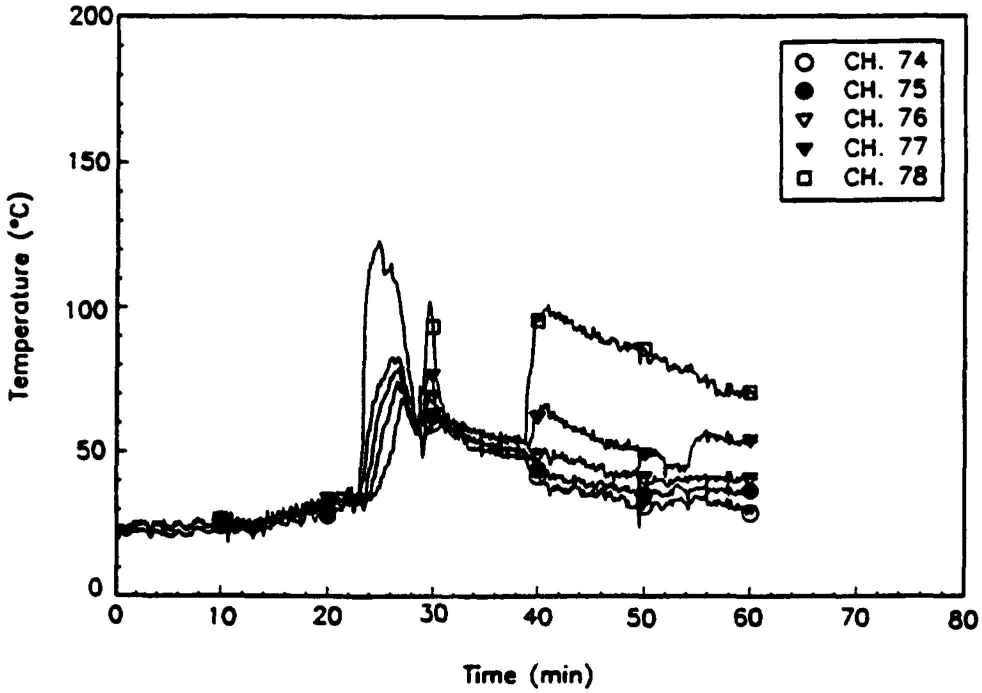

Fig. A79 — RICER 1 air temperatures aft, COL_9

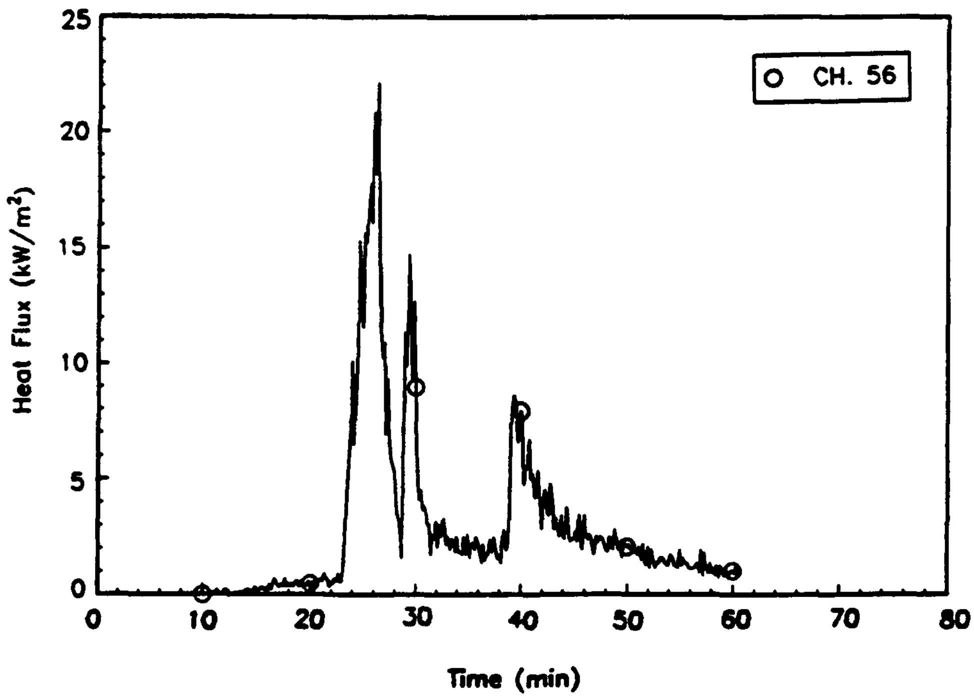

Fig. A80 — Total heat flux at RICER 1 overhead, COL_9

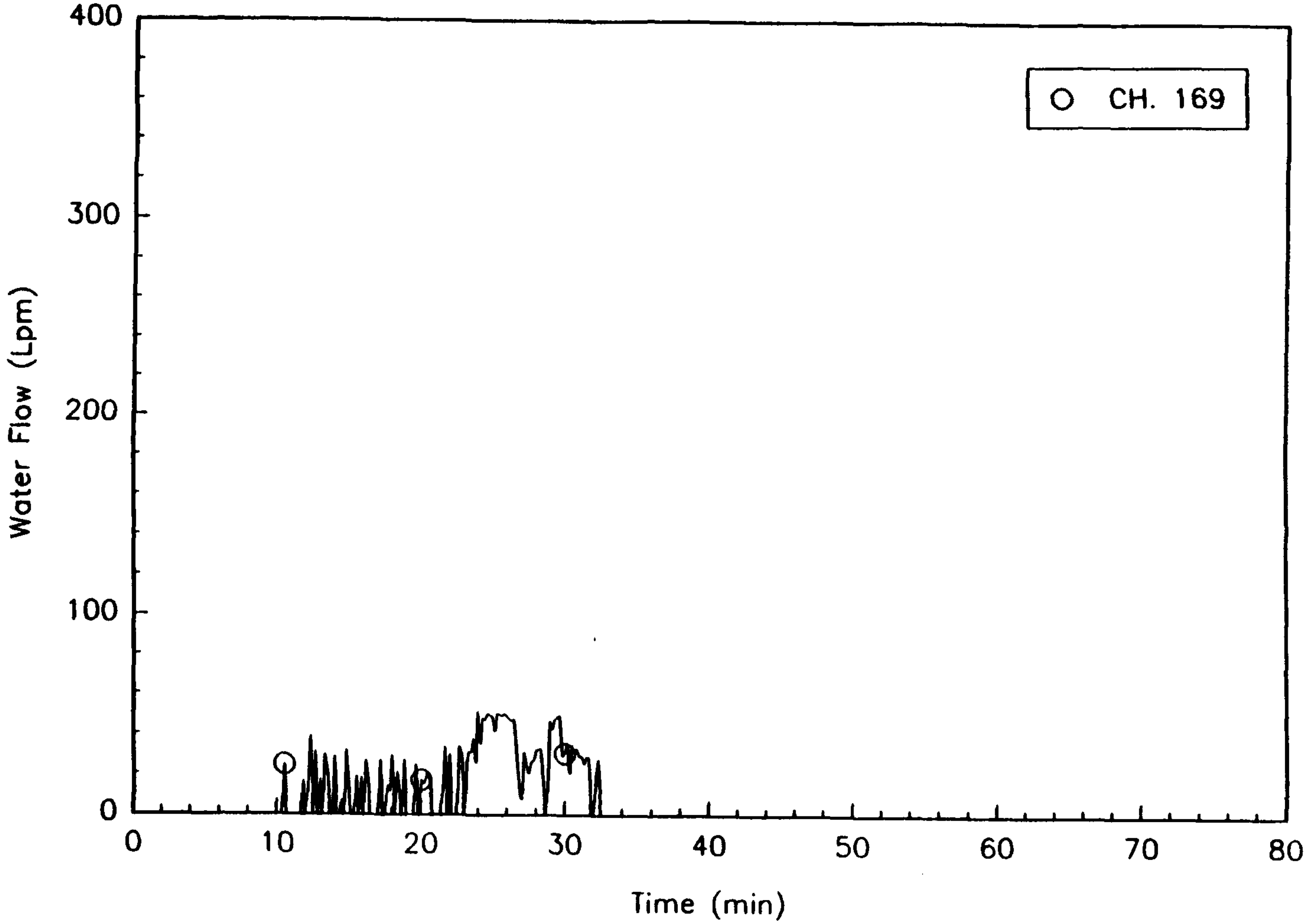

Fig. A81 — Water flow from cooling handline, COL_9

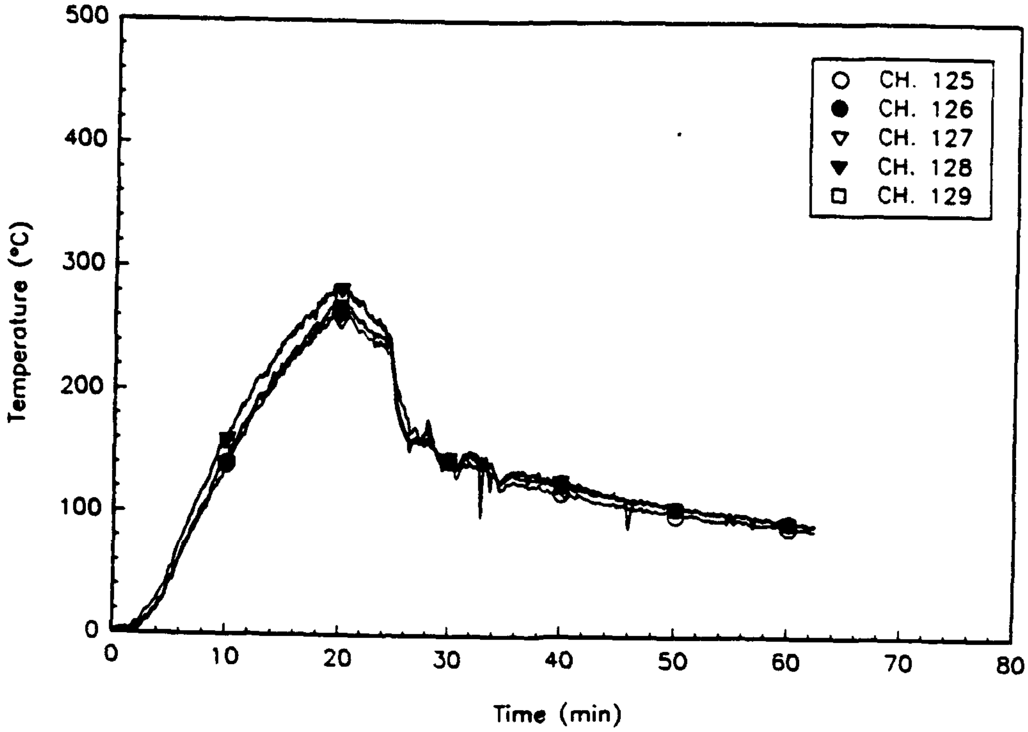

Fig. A82 — RICER 2 air temperatures forward, COL_10

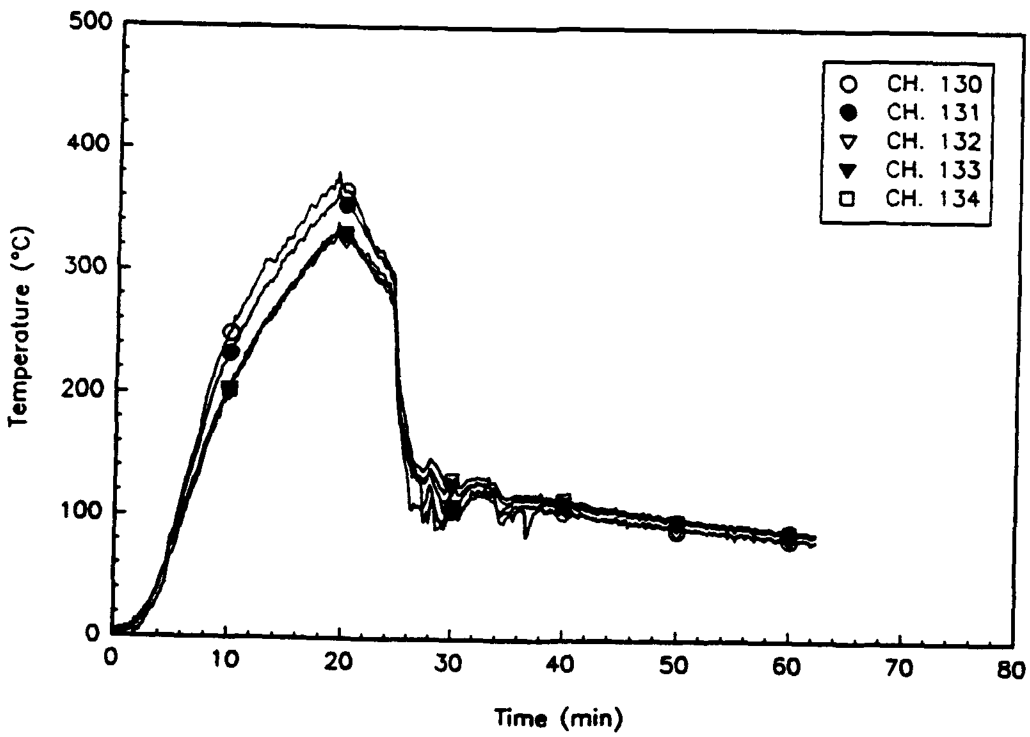

Fig. A83 — RICER 2 air temperatures aft, COL_10

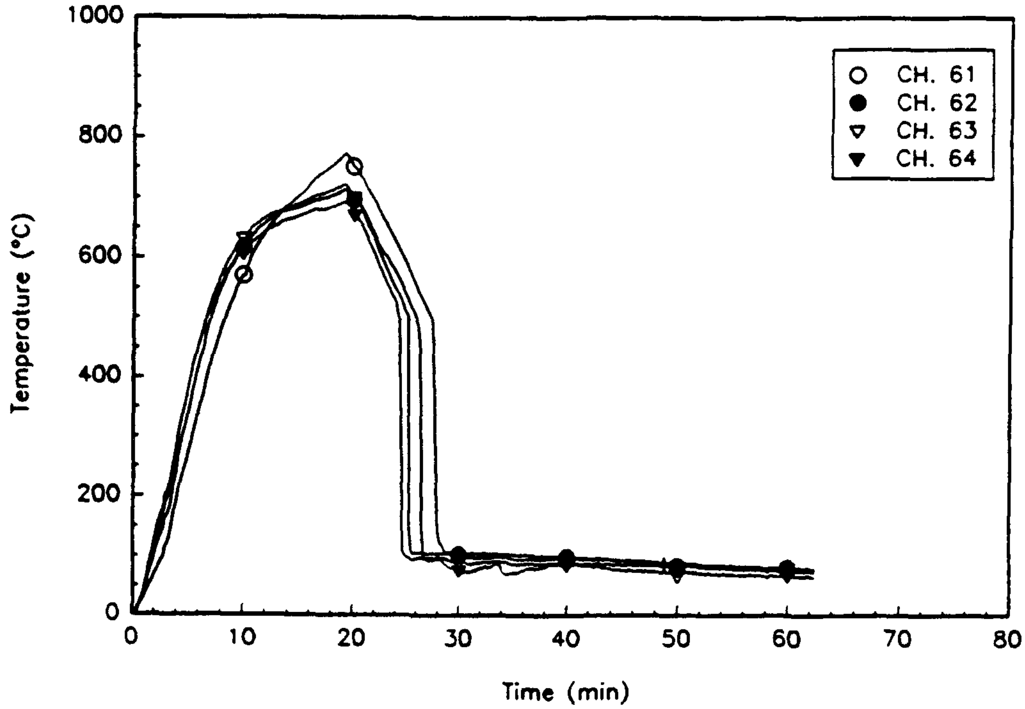

Fig. A84 — RICER 2 deck temperatures aft, COL_10

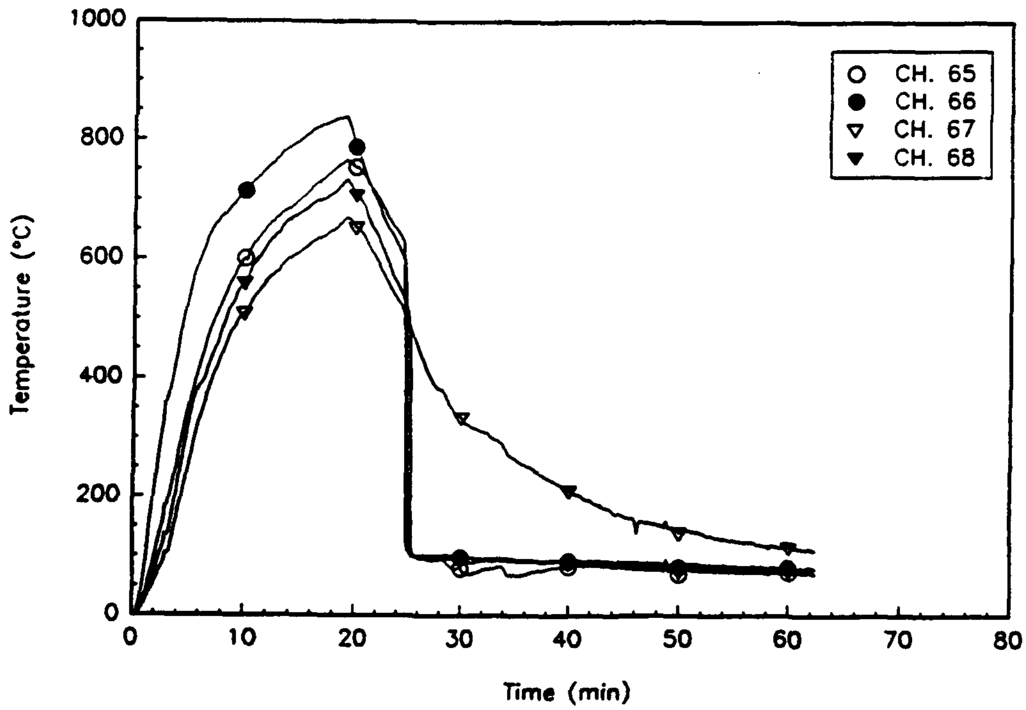

Fig. A85 — RICER 2 deck temperatures forward, COL_10

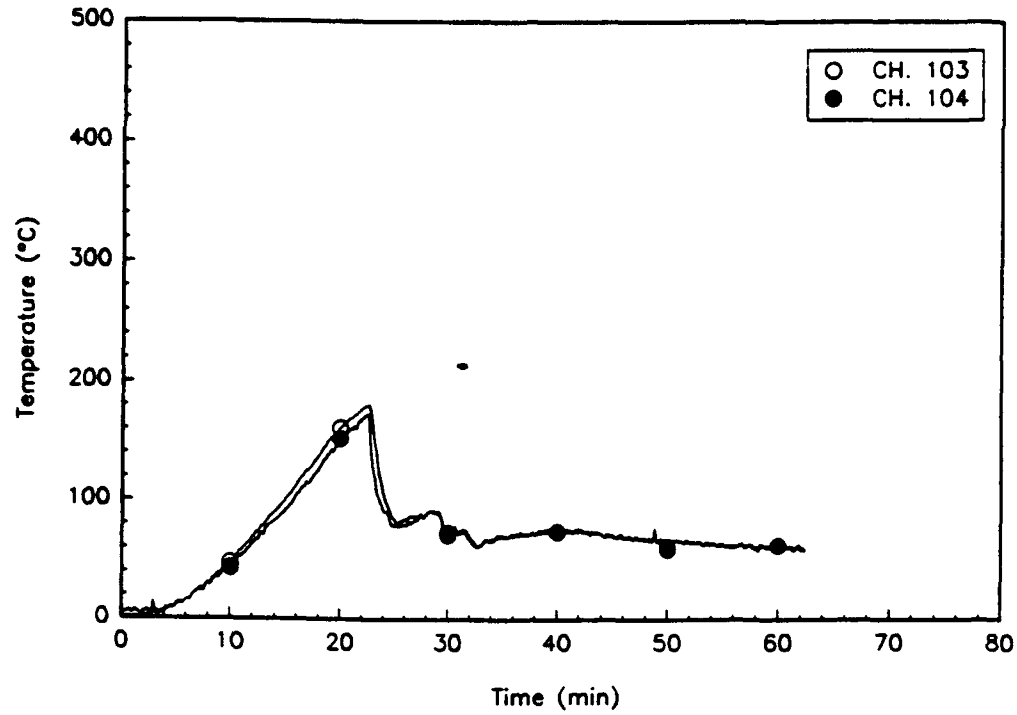

Fig. A86 — CIC deck temperatures, COL_10

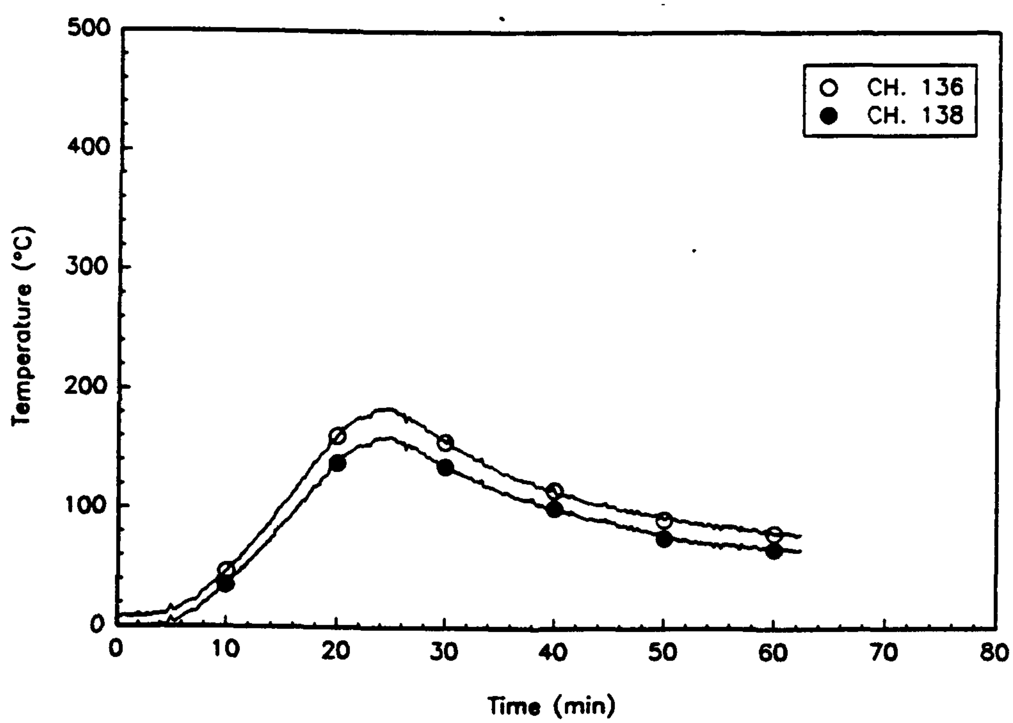

Fig. A87 — FR 88 bulkhead temperatures (RICER 2 side), COL_10

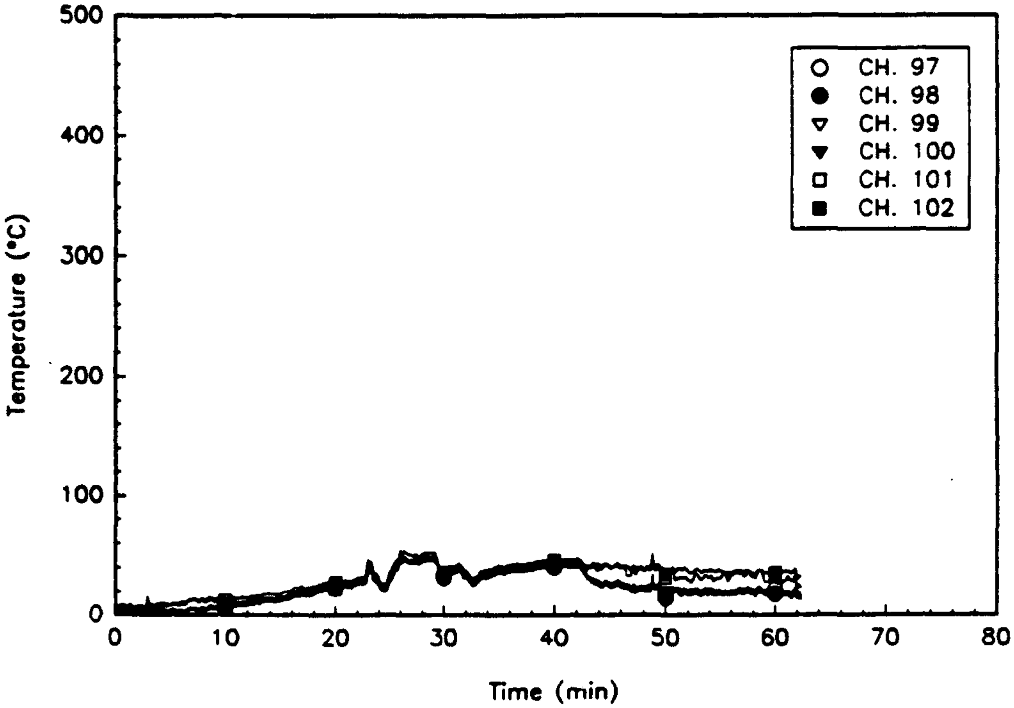

Fig. A88 – CIC air temperatures aft, COL_10

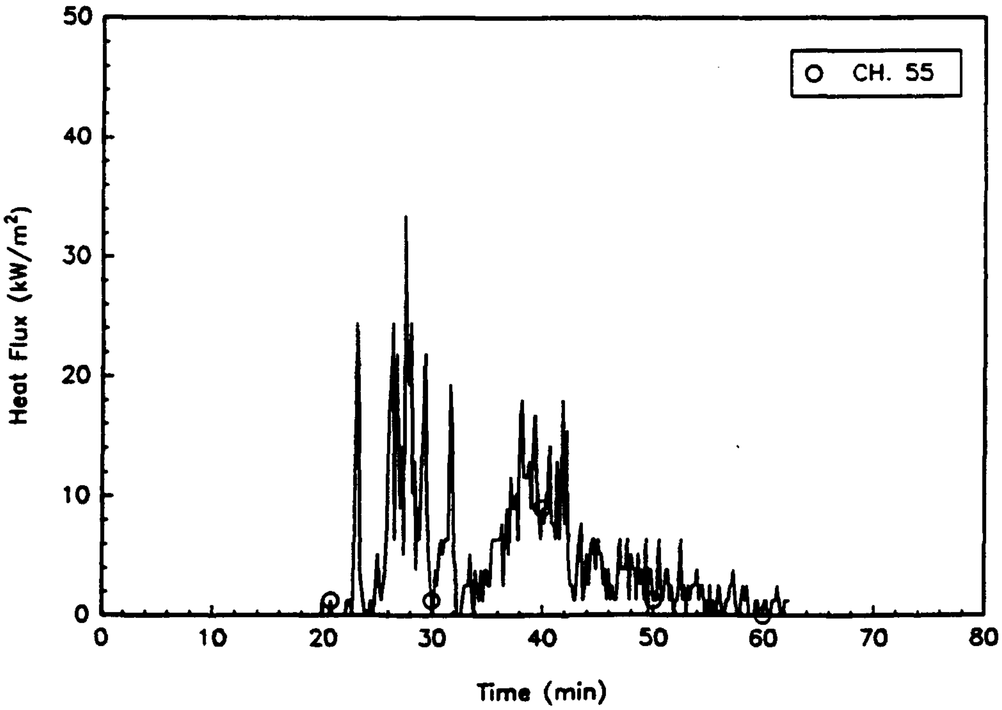

Fig. A89 – Total heat flux at CIC overhead, COL_10

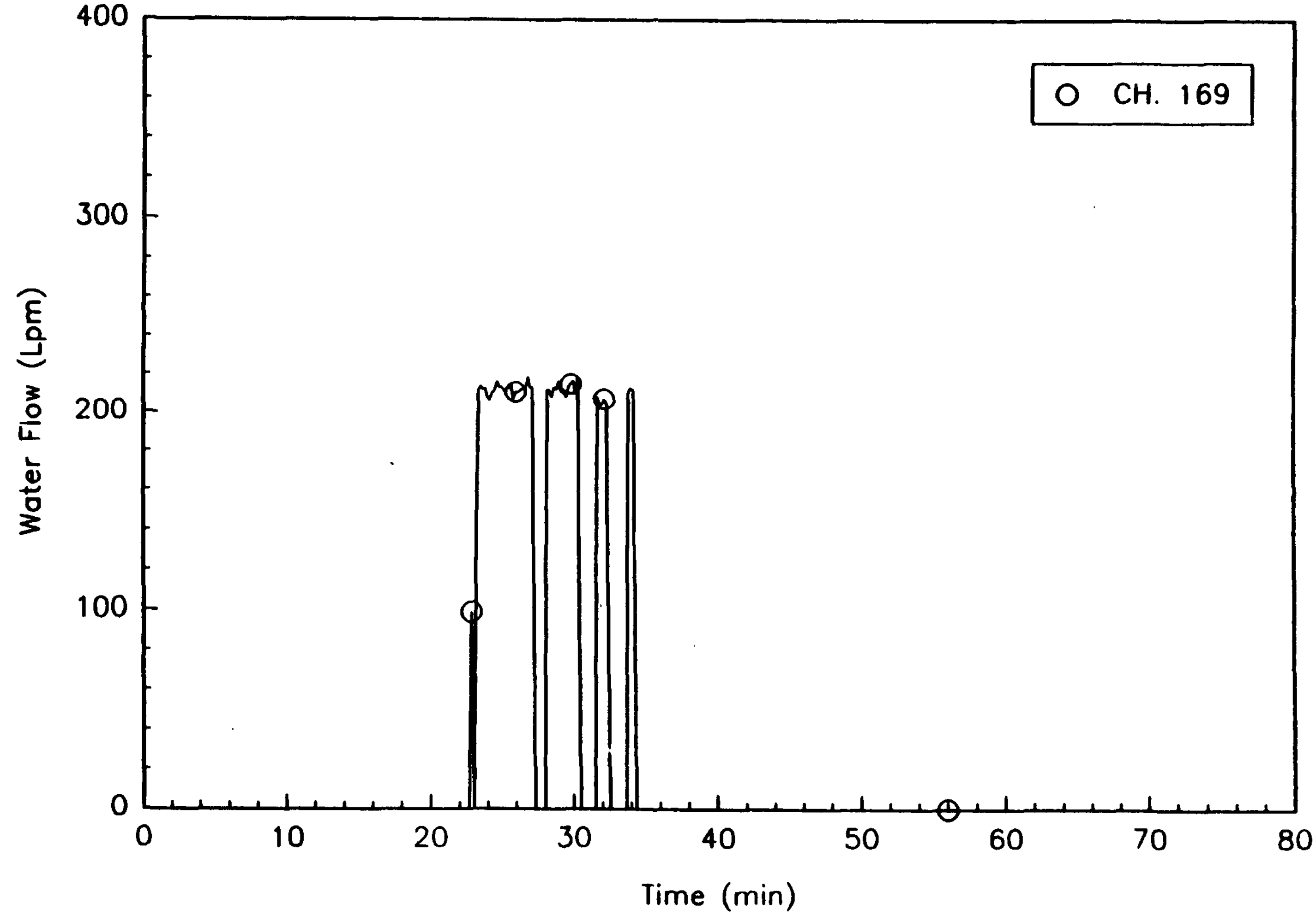

Fig. A90 — Water flow from cooling handline, COL_10

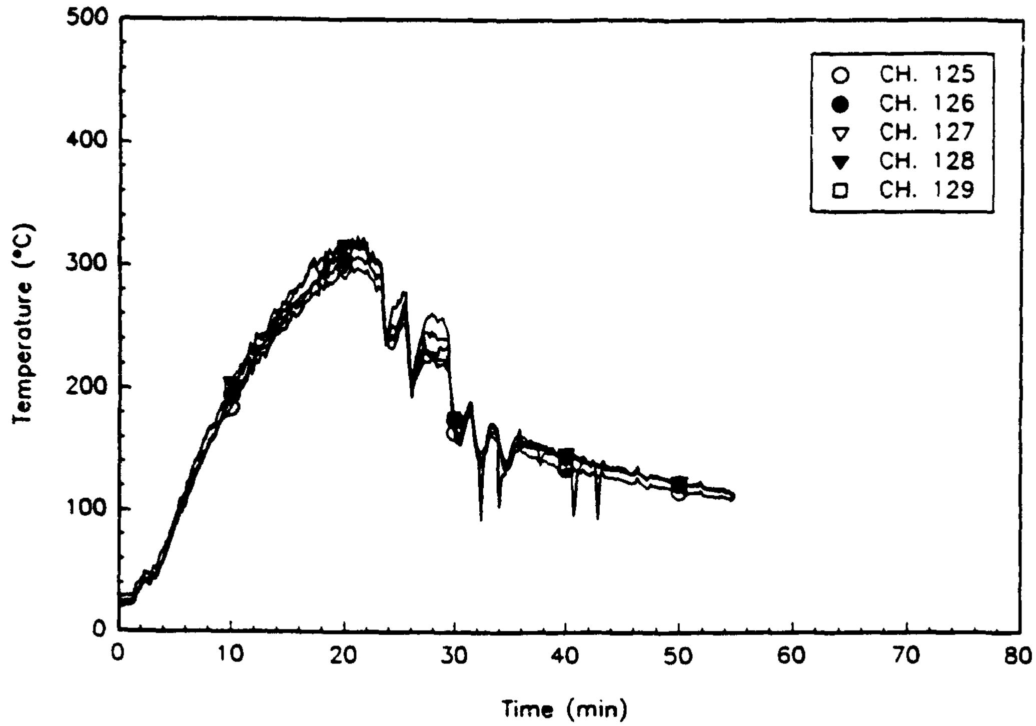

Fig. A91 – RICER 2 air temperatures forward, COL_11

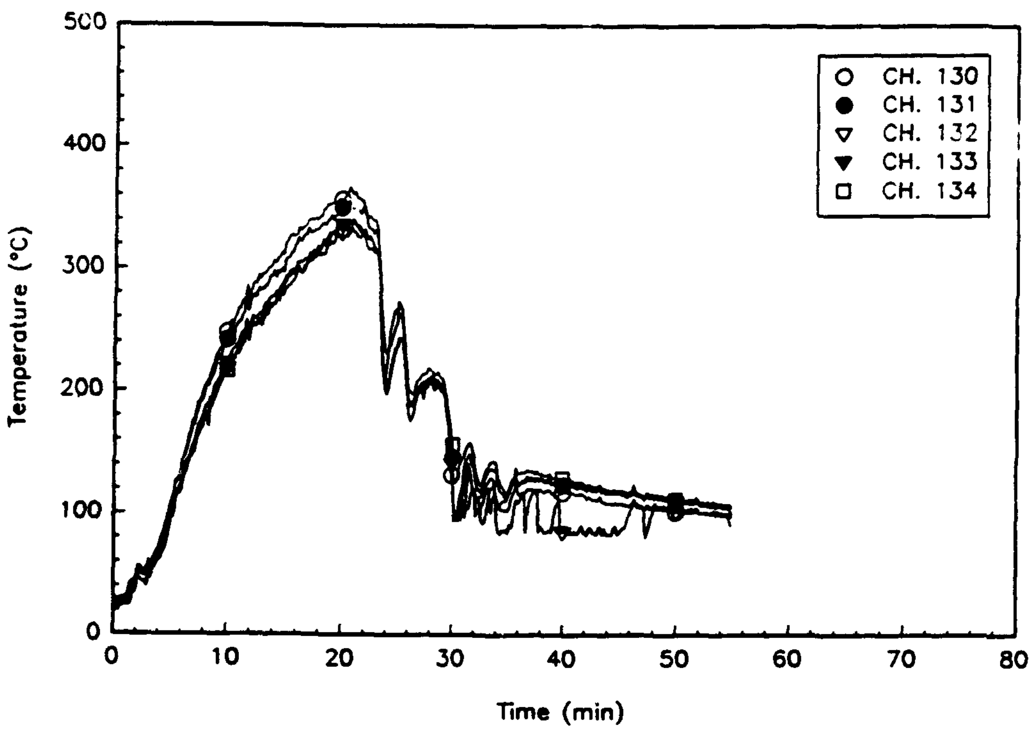

Fig. A92 – RICER 2 air temperatures aft, COL_11

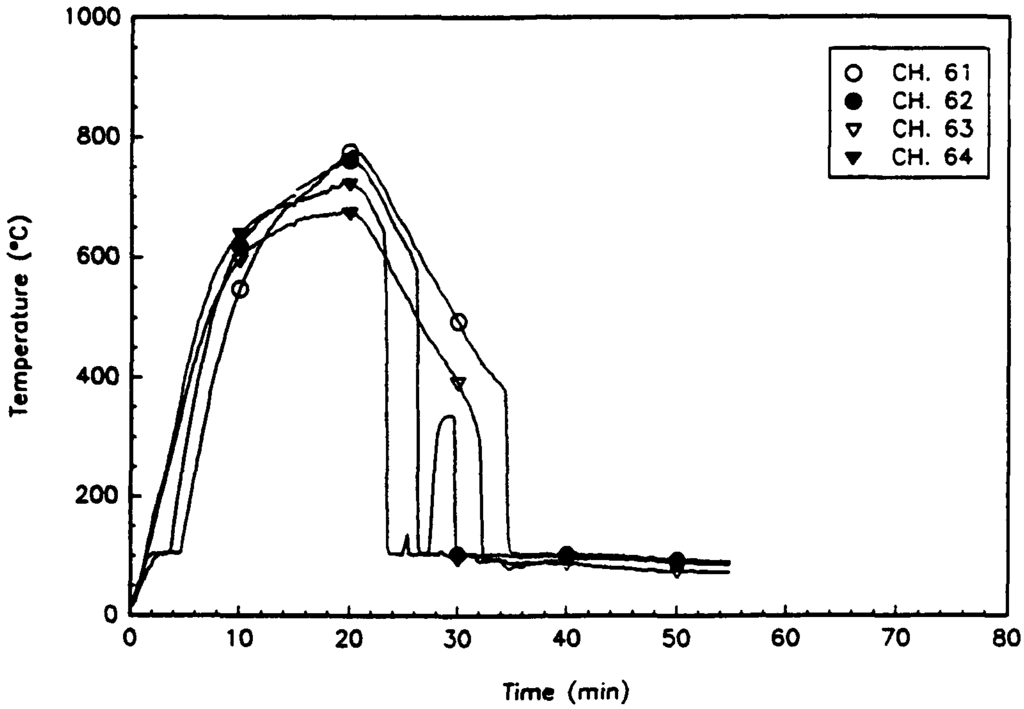

Fig. A93 — RICER 2 deck temperatures aft, COL_11

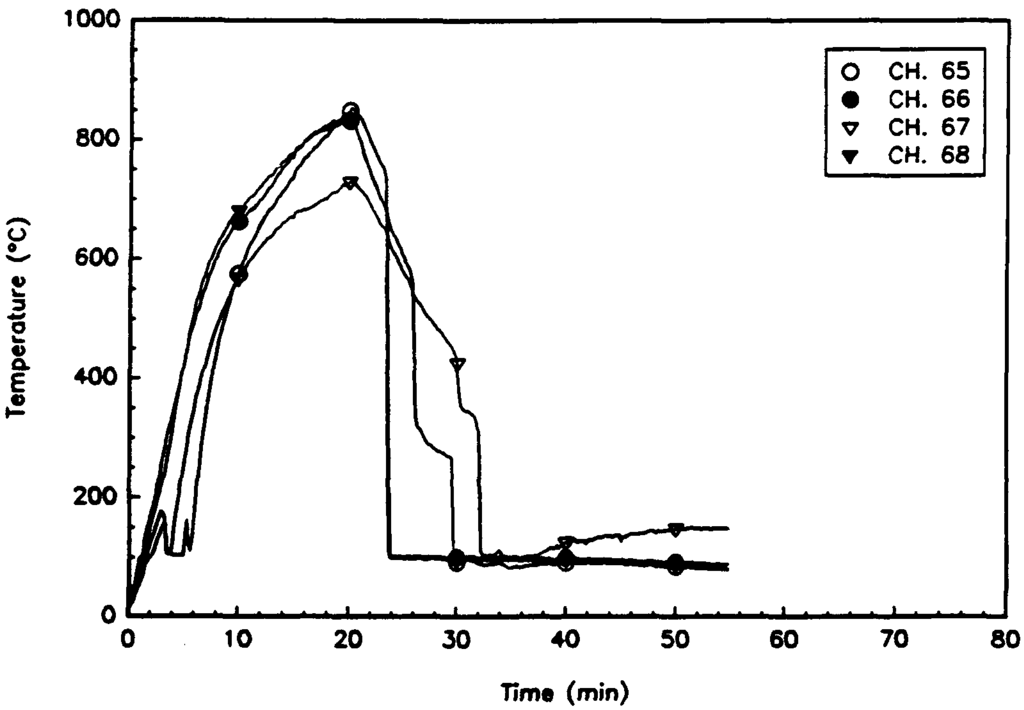

Fig. A94 — RICER 2 deck temperatures forward, COL_11

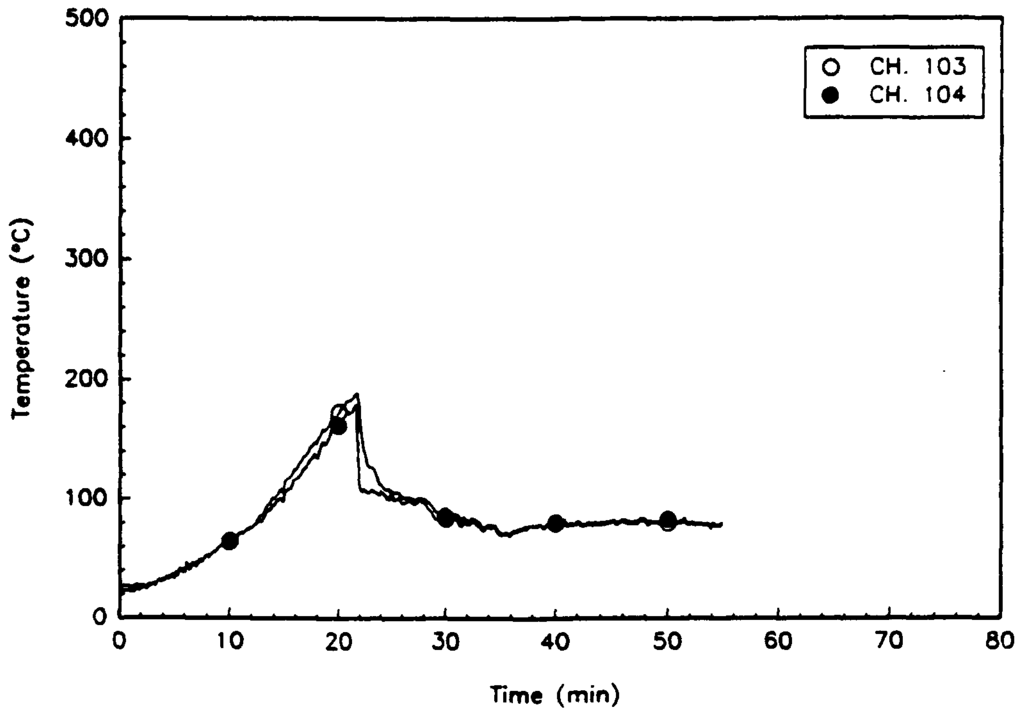

Fig. A95 – CIC deck temperatures, COL_11

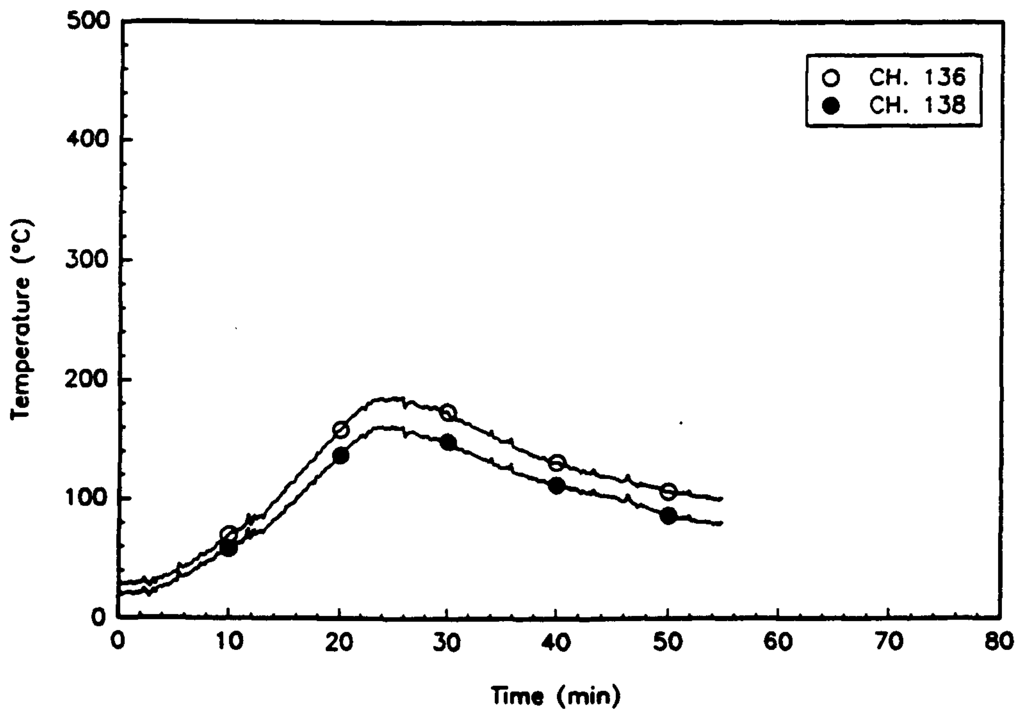

Fig. A96 – FR 88 bulkhead temperatures (RICER 2 side), COL_11

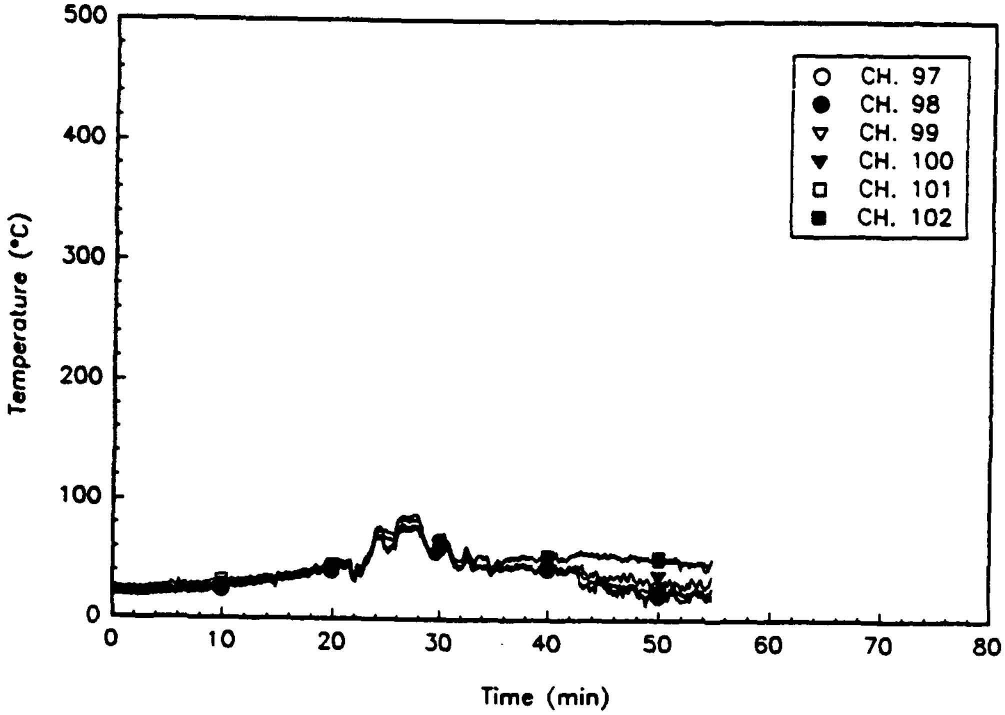

Fig. A97 – CIC air temperatures aft, COL_11

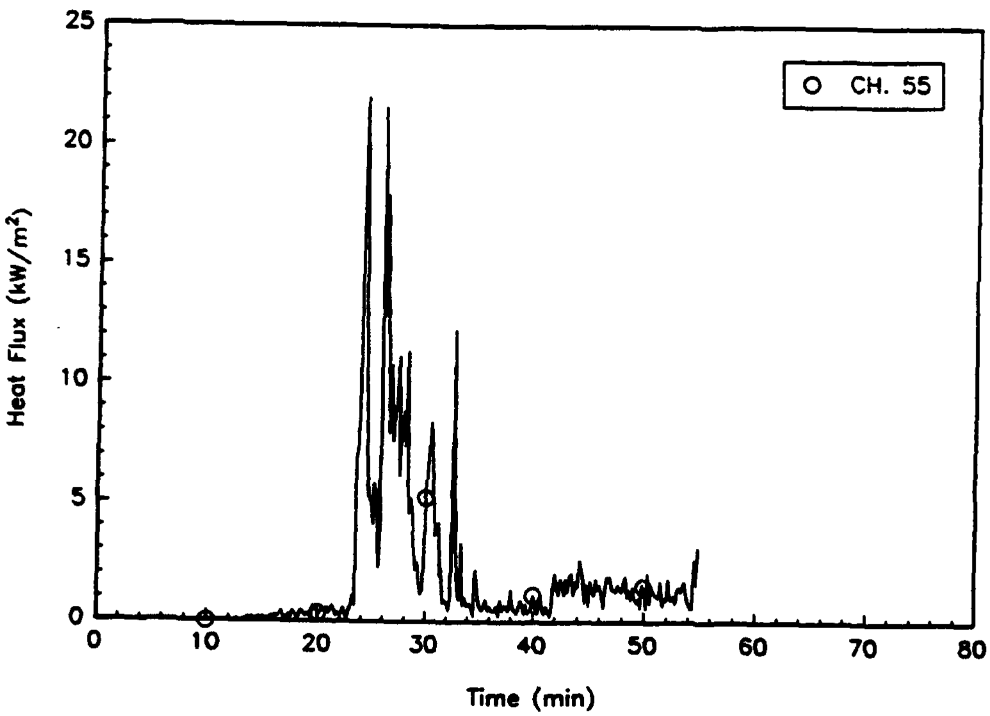

Fig. A98 – Total heat flux at CIC overhead, COL_11

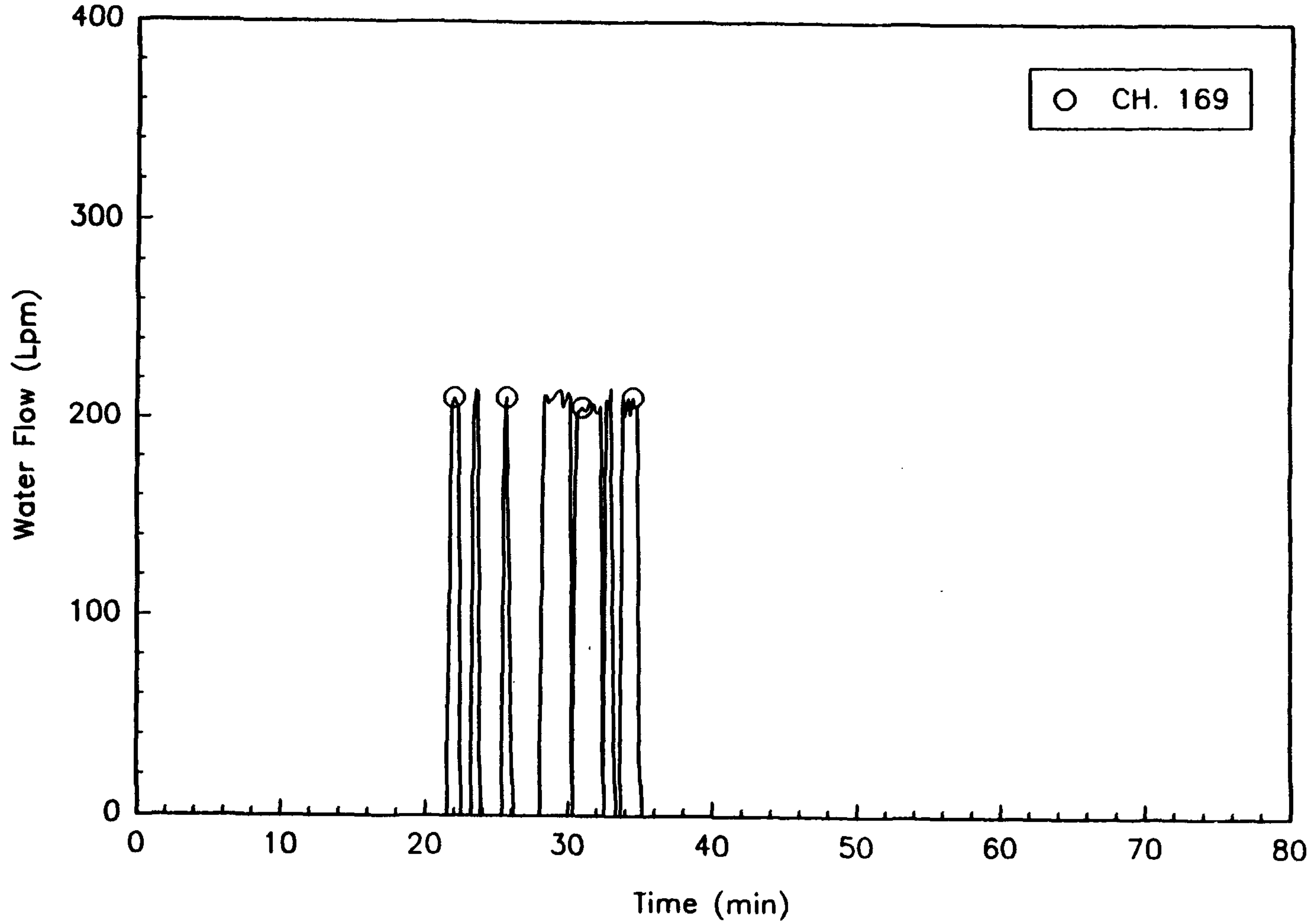

Fig. A99 – Water flow from cooling handline, COL_11

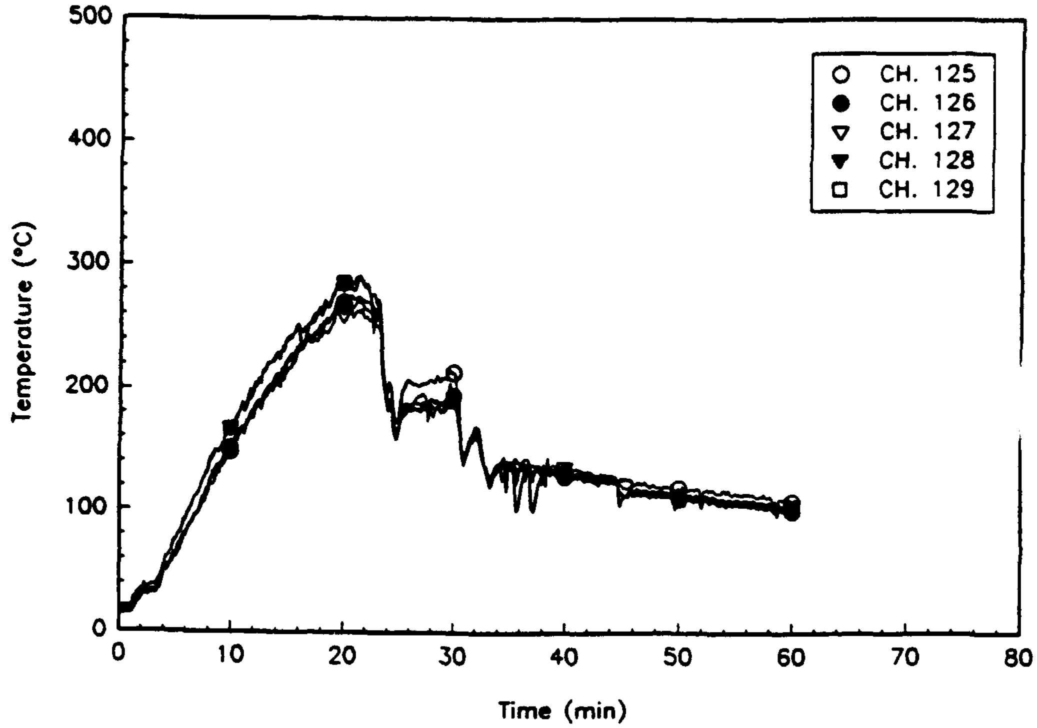

Fig. A100 — RICER 2 air temperatures forward, COL_12

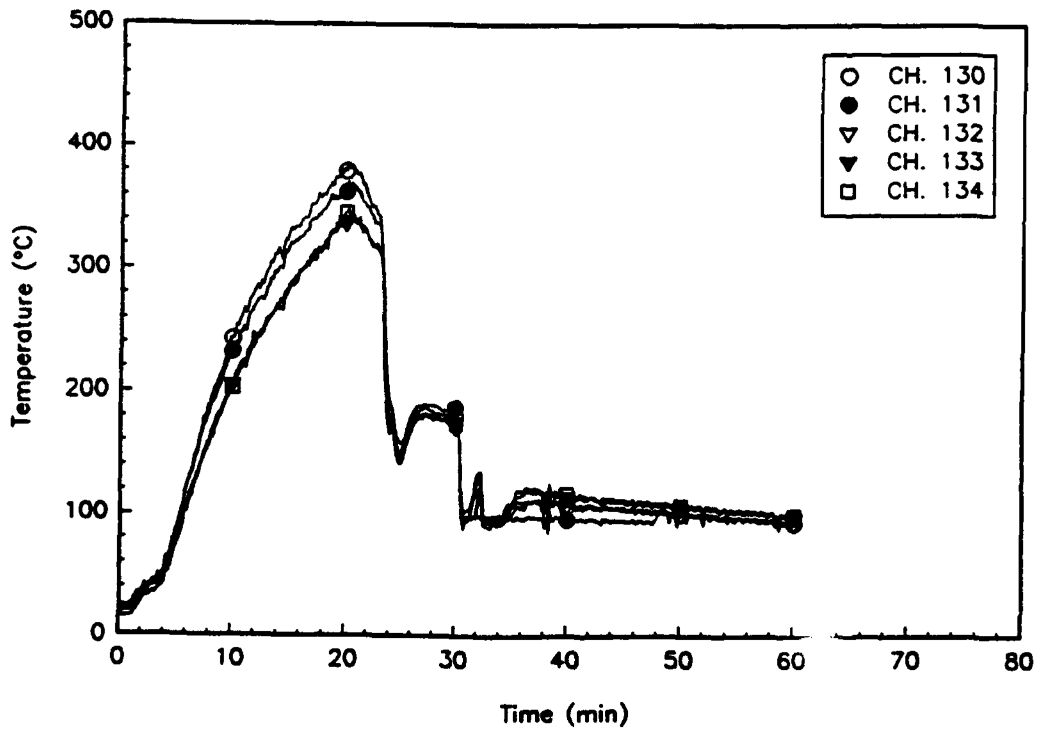

Fig. A101 — RICER 2 air temperatures aft, COL_12

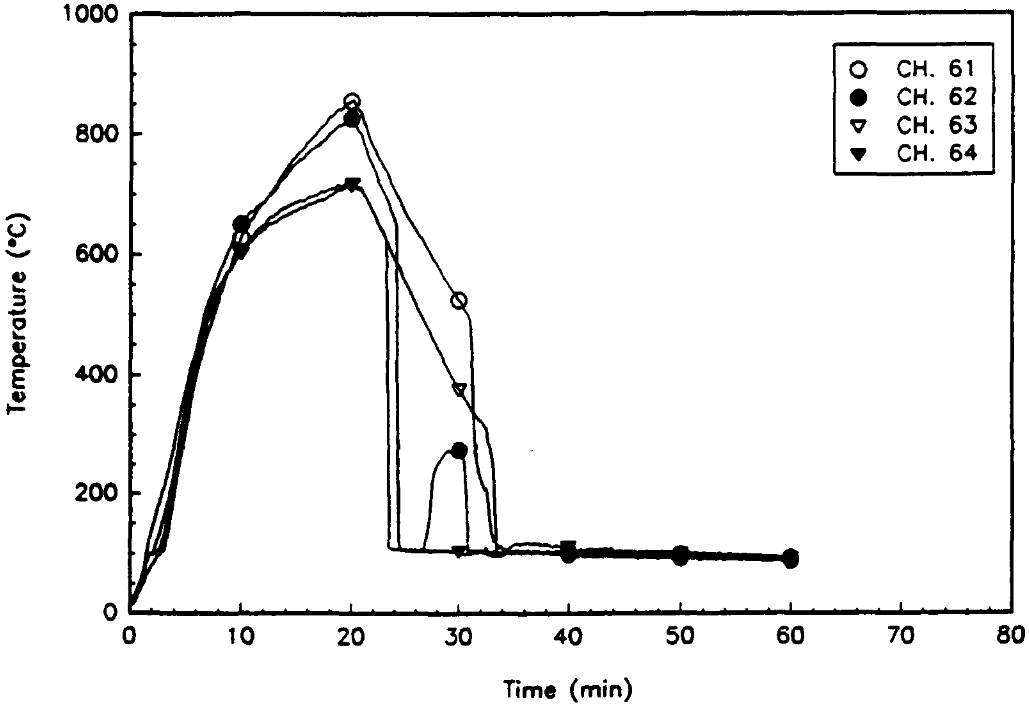

Fig. A102 – RICER 2 deck temperatures aft, COL_12

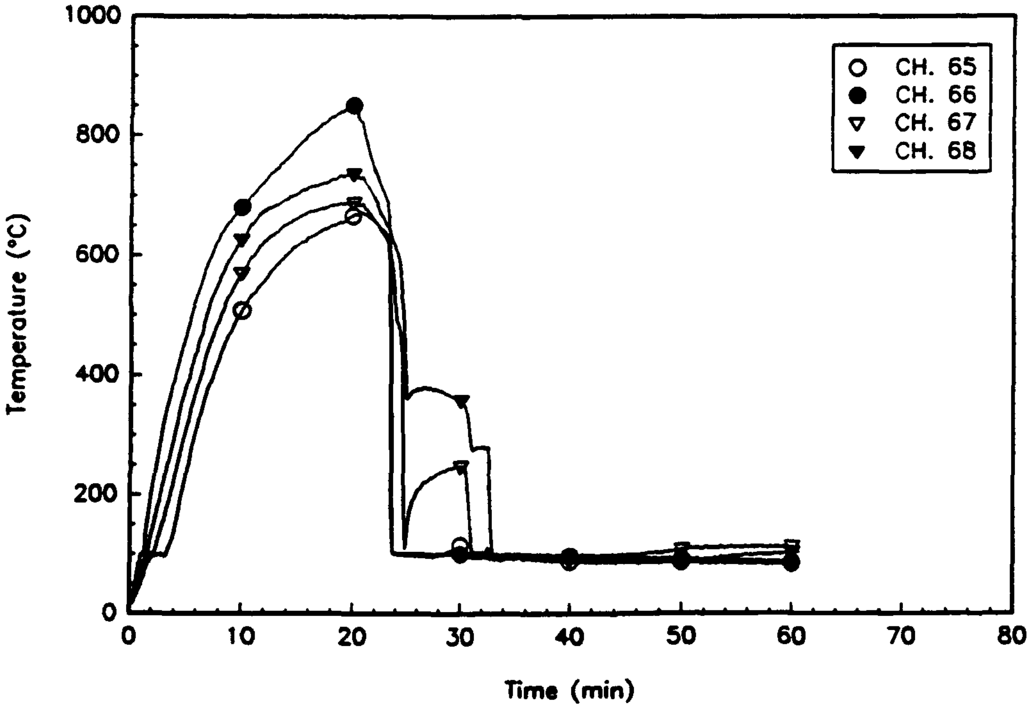

Fig. A103 – RICER 2 deck temperatures forward, COL_12

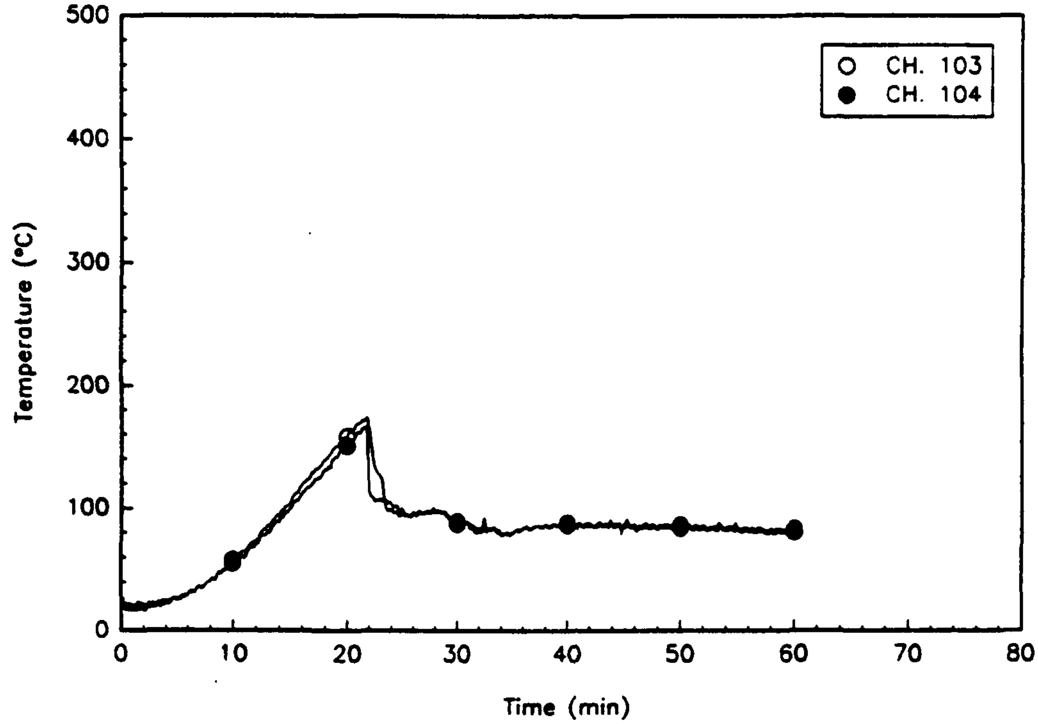

Fig. A104 – CIC deck temperatures, COL_12

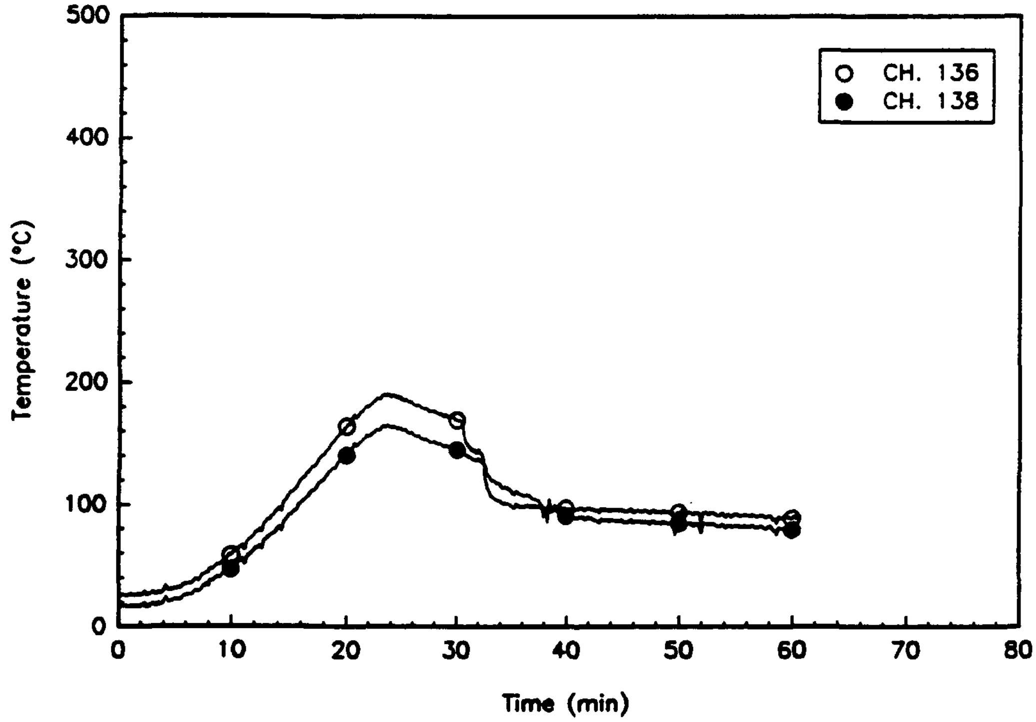

Fig. A105 – FR 88 bulkhead temperatures (RICER 2 side), COL_12

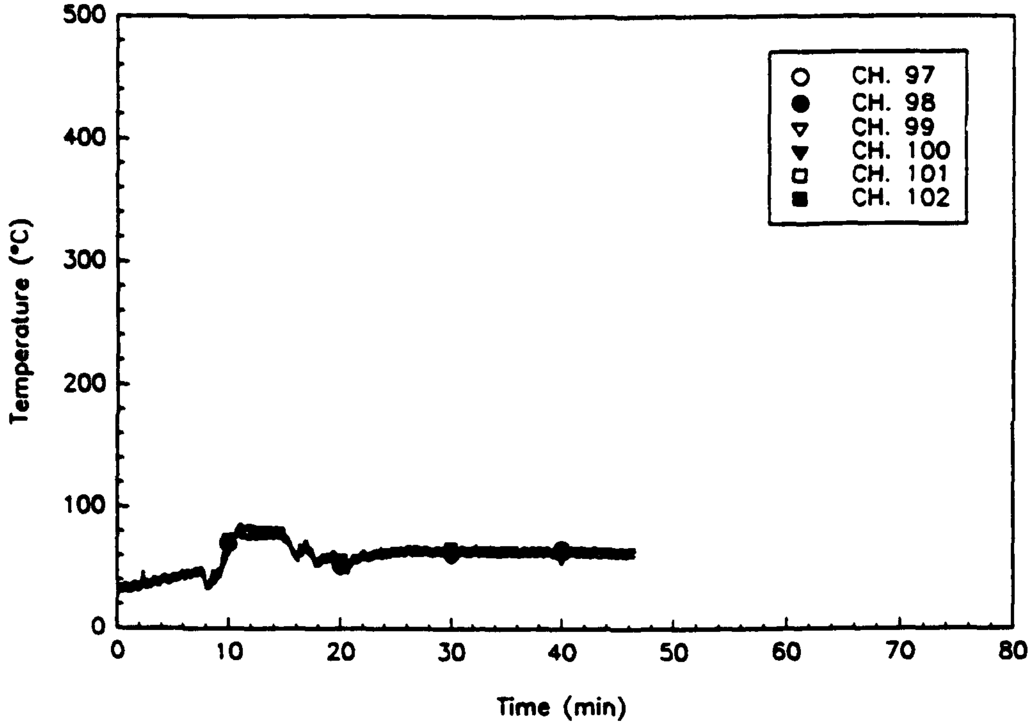

Fig. A106 – CIC air temperature aft, COL_12

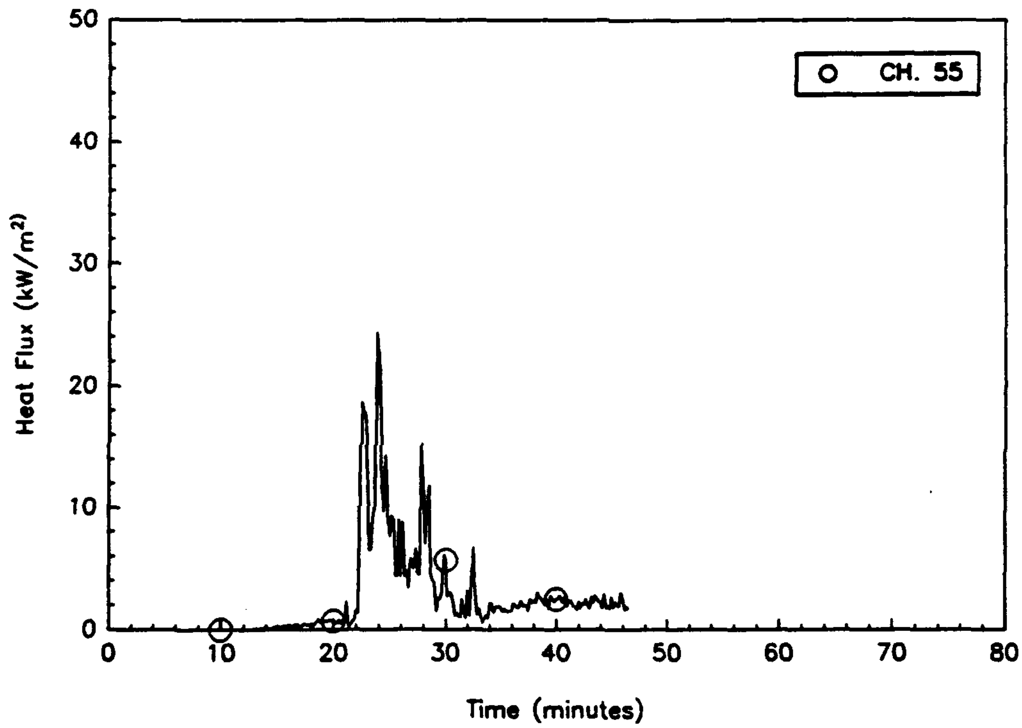

Fig. A107 – Total heat flux at CIC overhead, COL_12

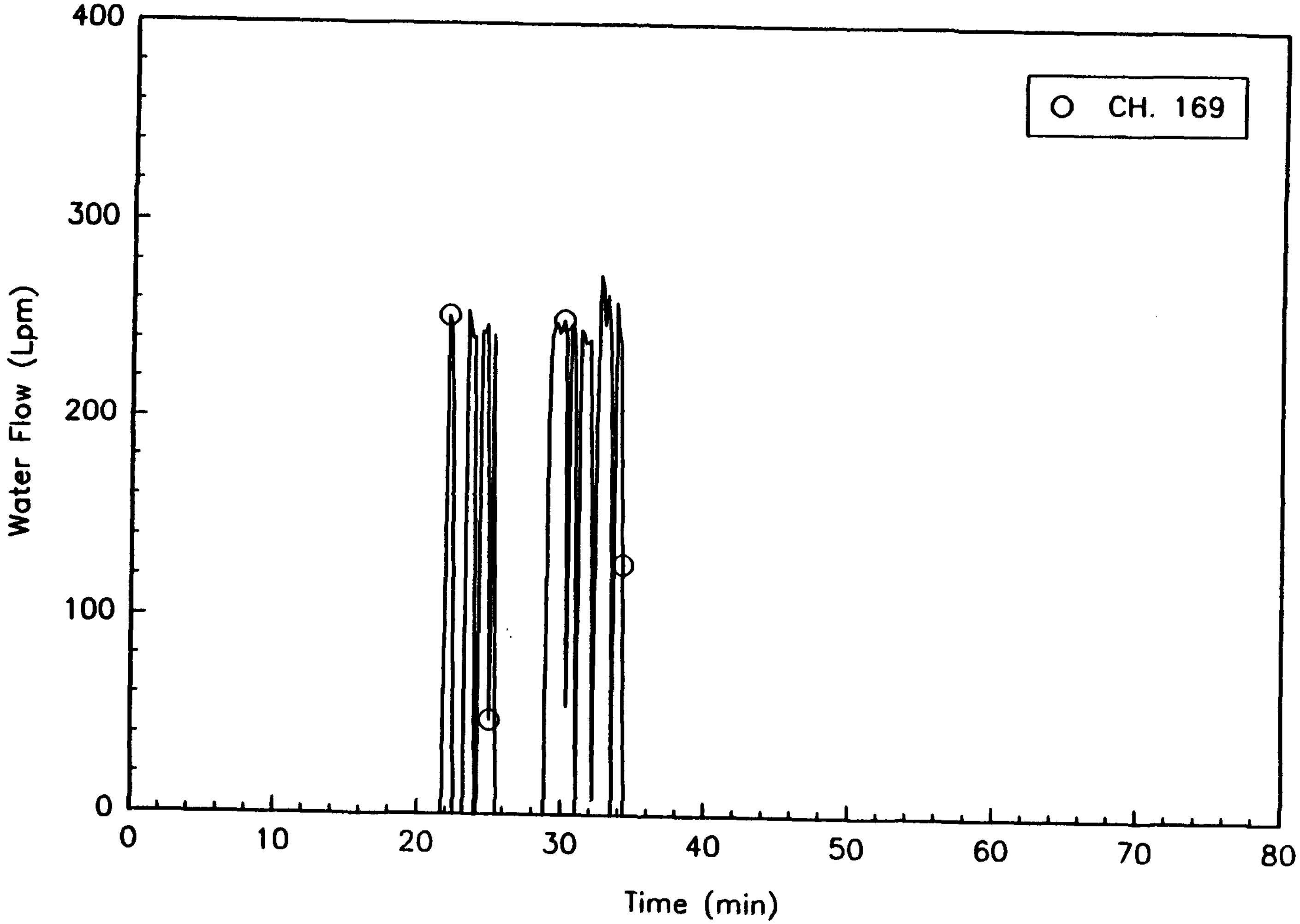

Fig. A108 — Water flow from cooling handline, COL_12

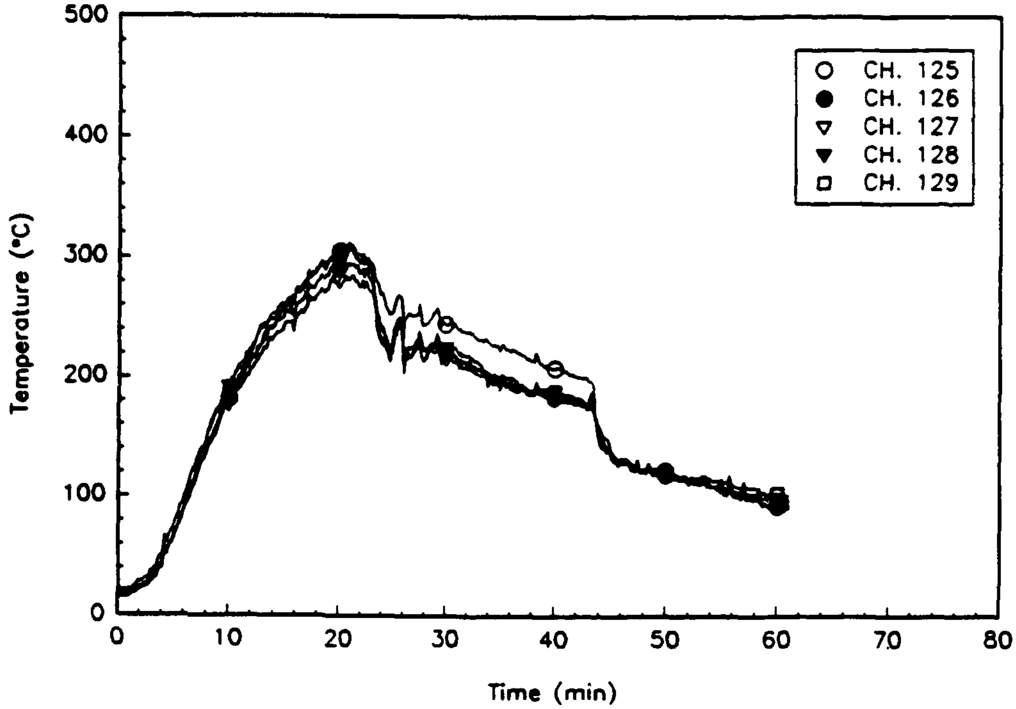

Fig. A109 — RICER 2 air temperatures forward, COL_13

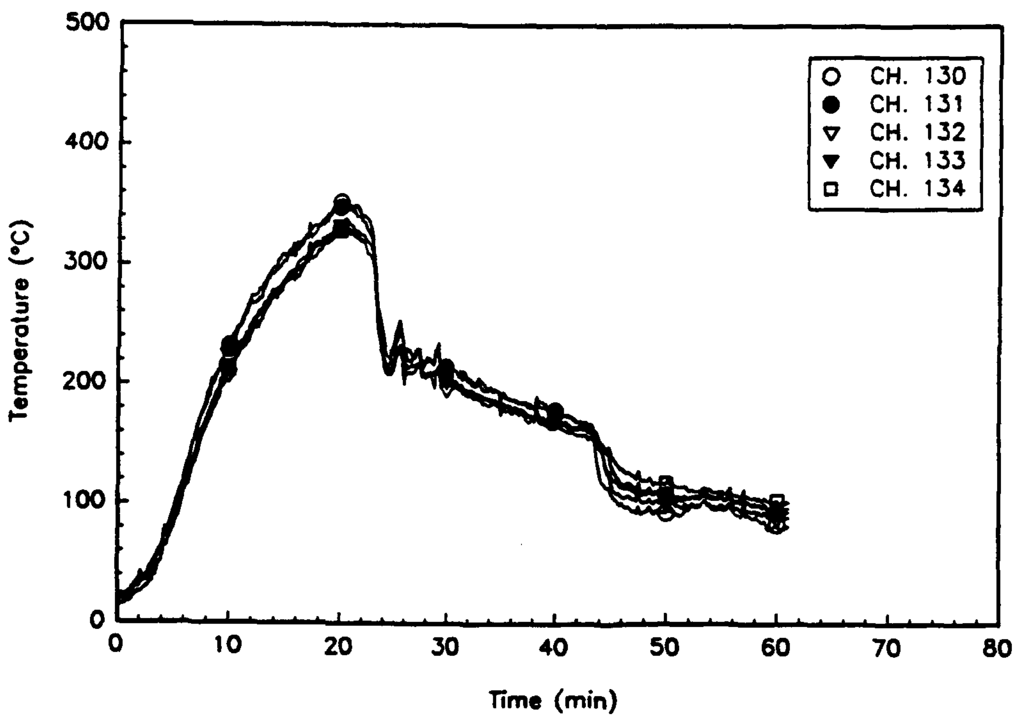

Fig. A110 — RICER 2 air temperatures aft, COL_13

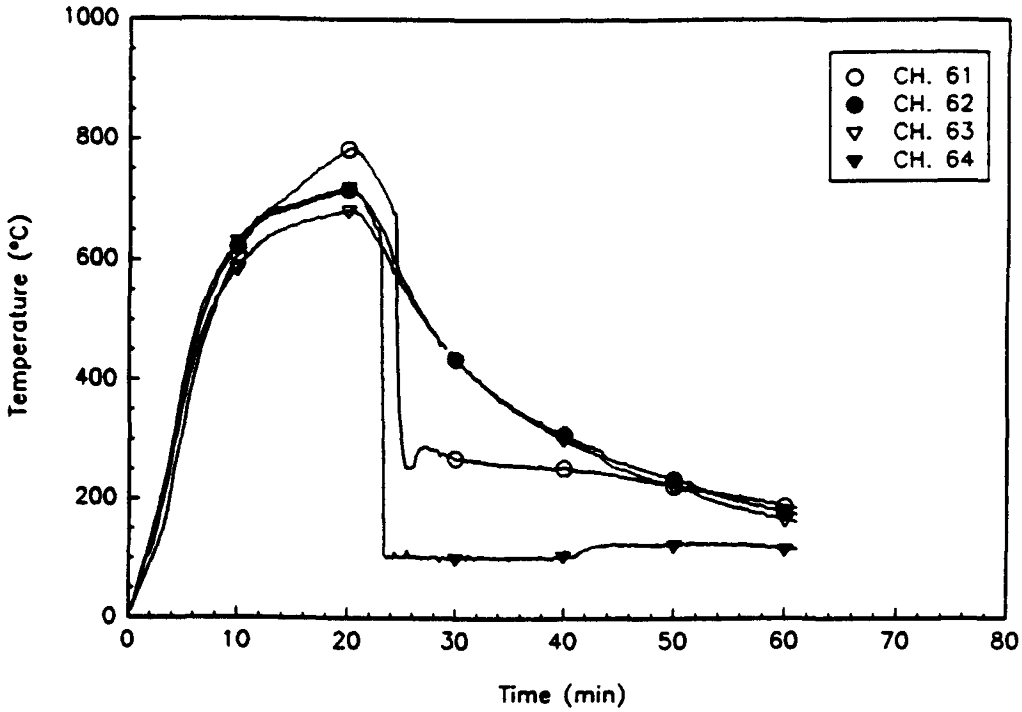

Fig. A111 — RICER 2 deck temperatures aft, COL_13

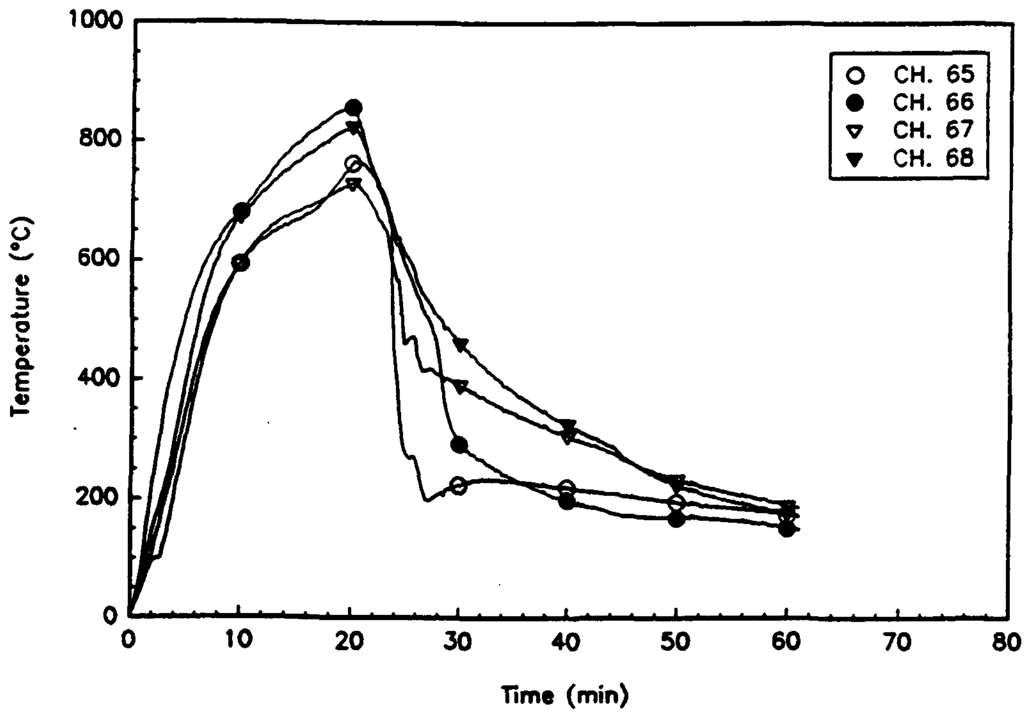

Fig. A112 — RICER 2 deck temperatures forward, COL_13

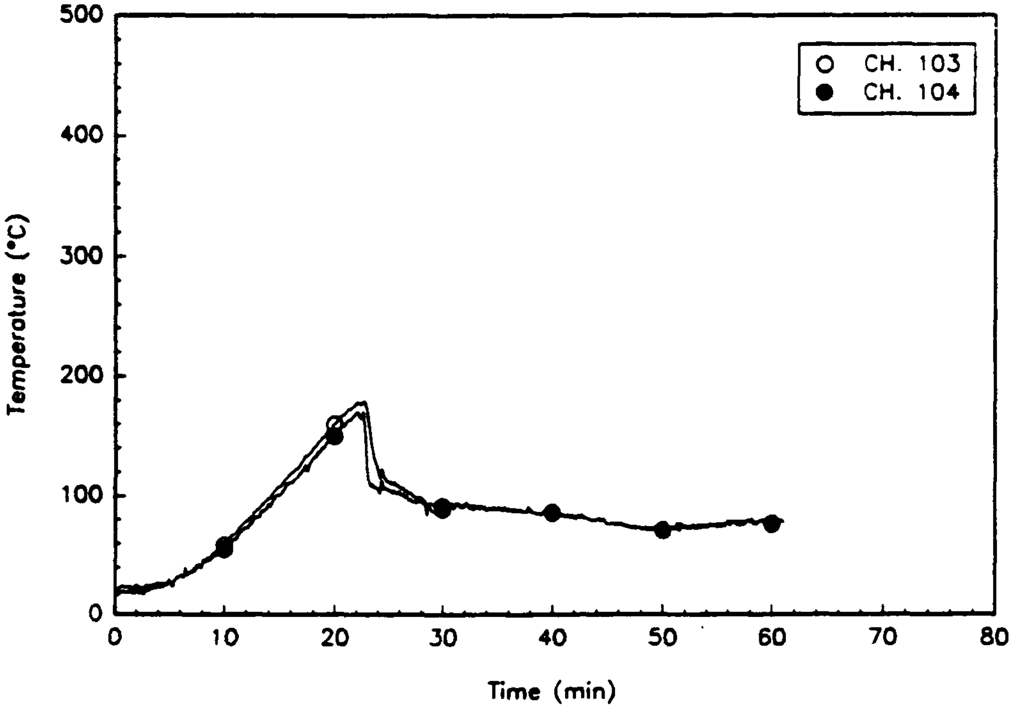

Fig. A113 – CIC deck temperatures, COL_13

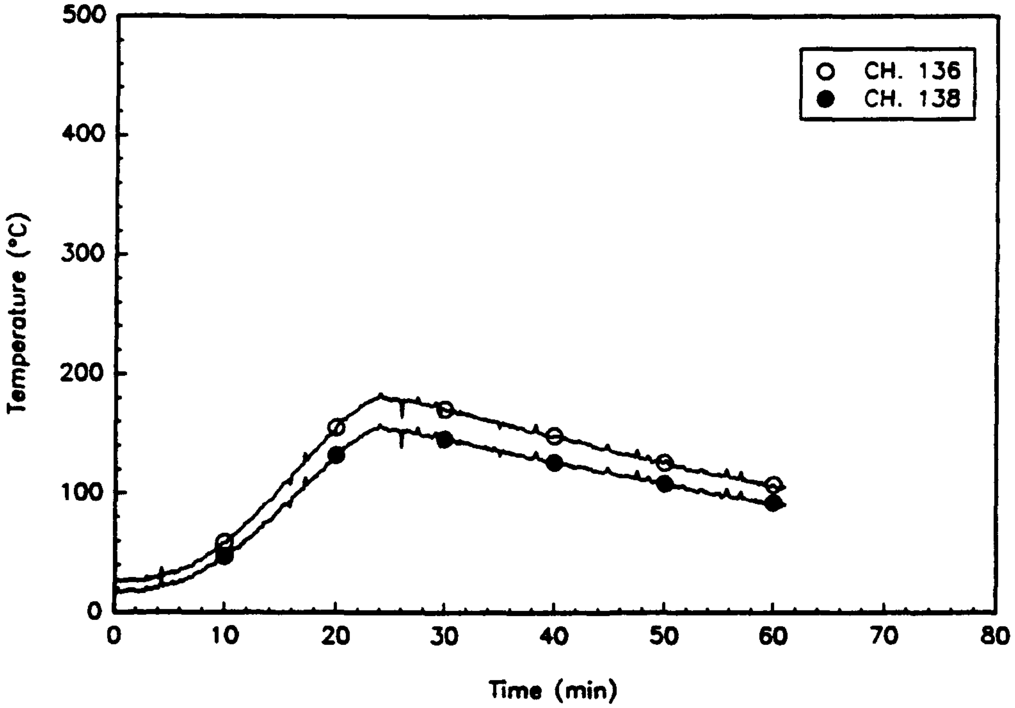

Fig. A114 – FR 88 bulkhead temperatures (RICER 2 side), COL_13

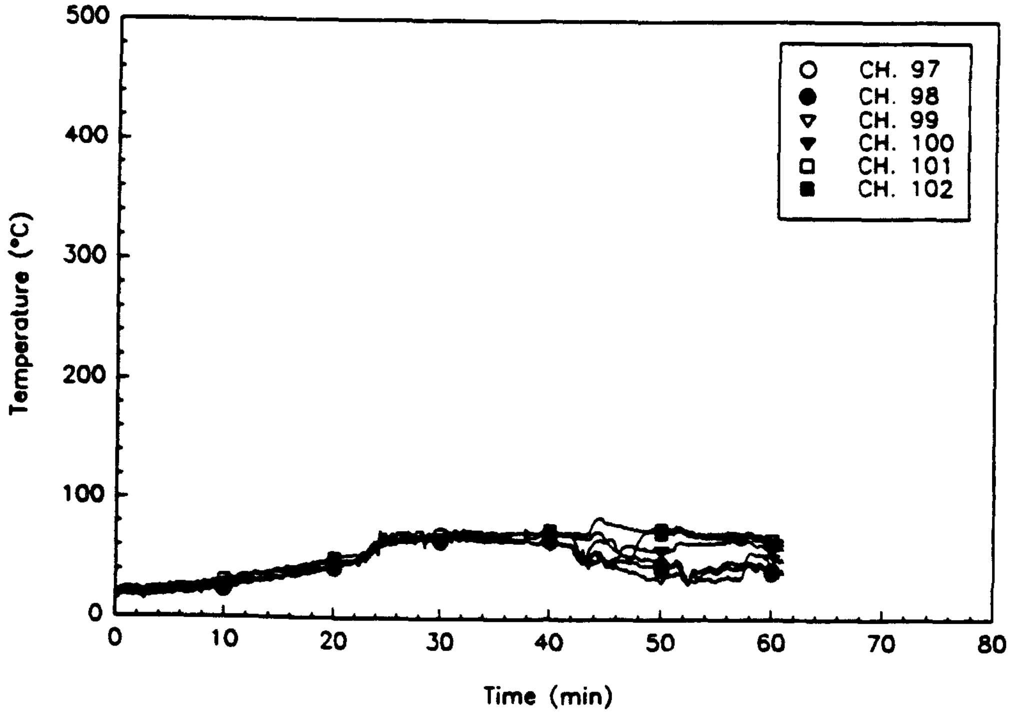

Fig. A115 – CIC air temperature aft, COL_13

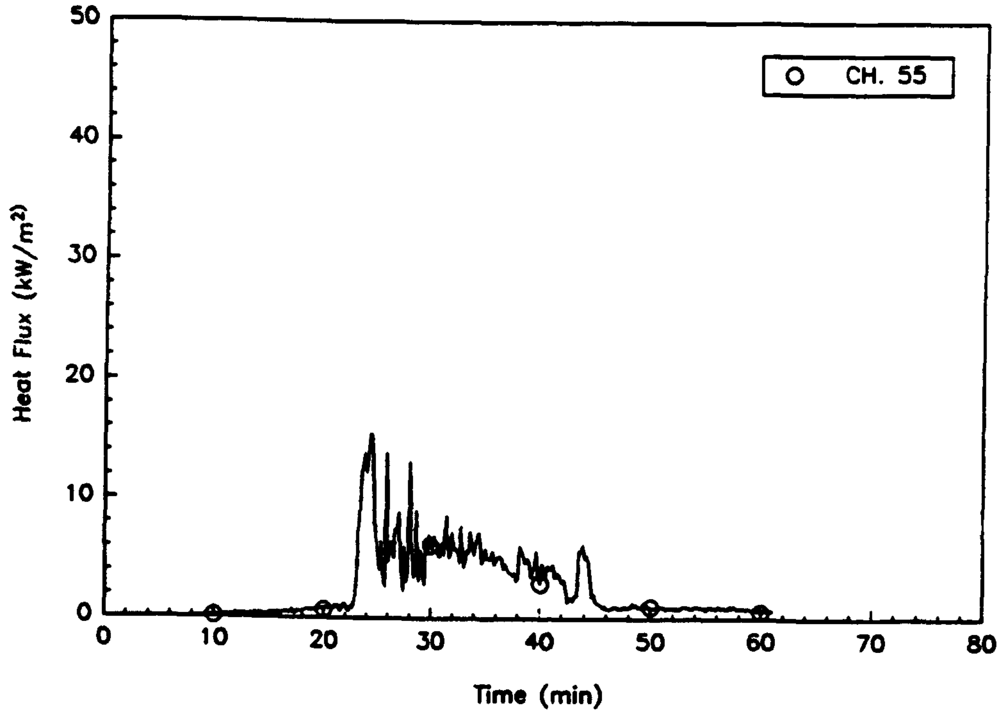

Fig. A116 – Total heat flux at CIC overhead, COL_13

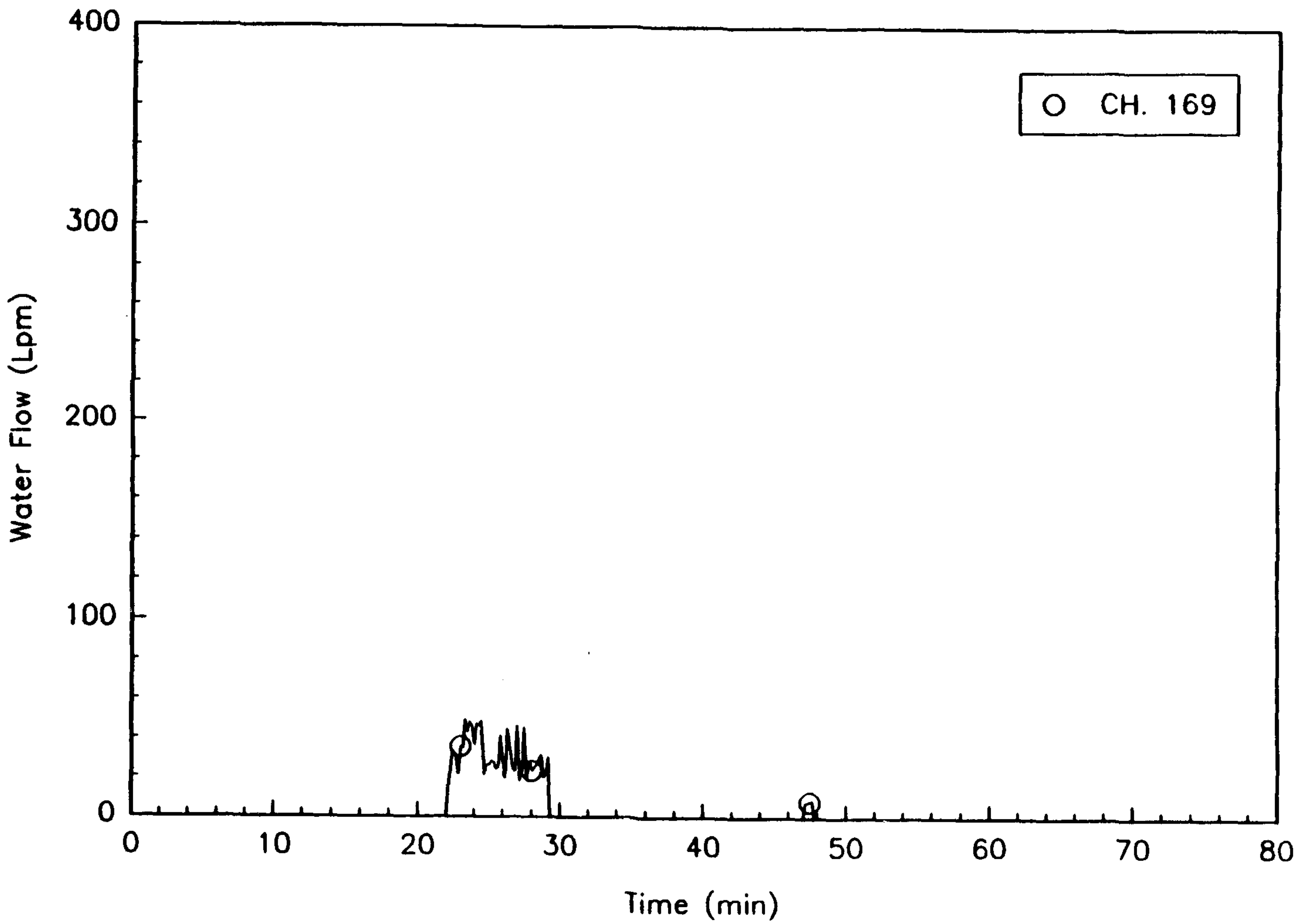

Fig. A117 – Water flow from cooling handline, COL_13

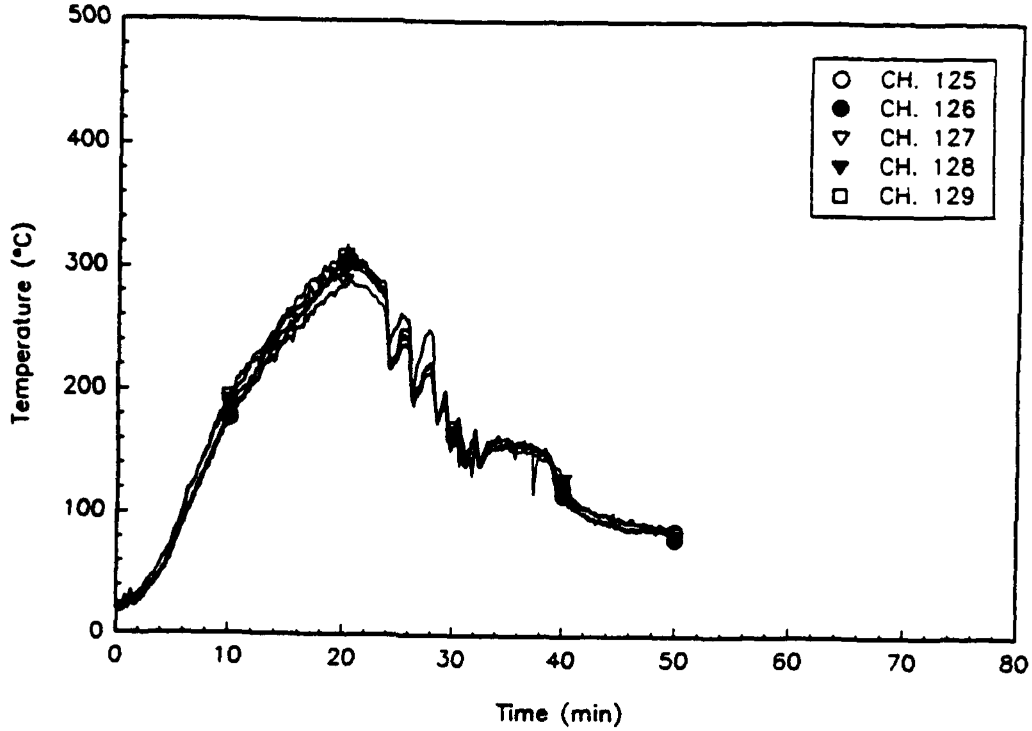

Fig. A118 – RICER 2 air temperatures forward, COL_14

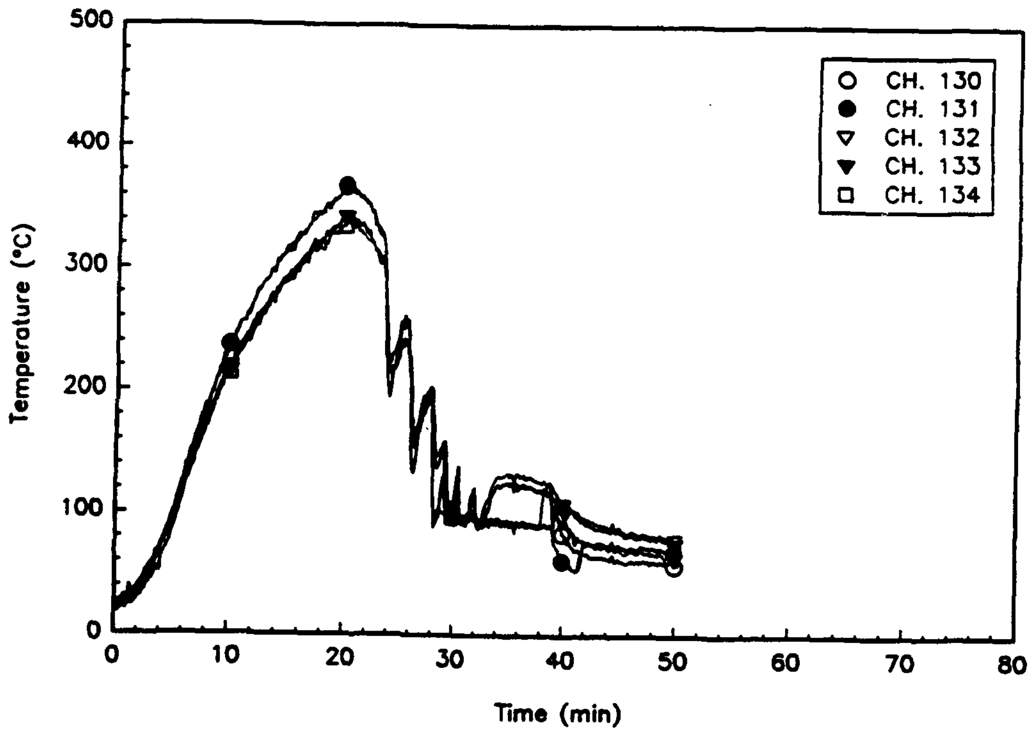

Fig. A119 – RICER 2 air temperatures aft, COL_14

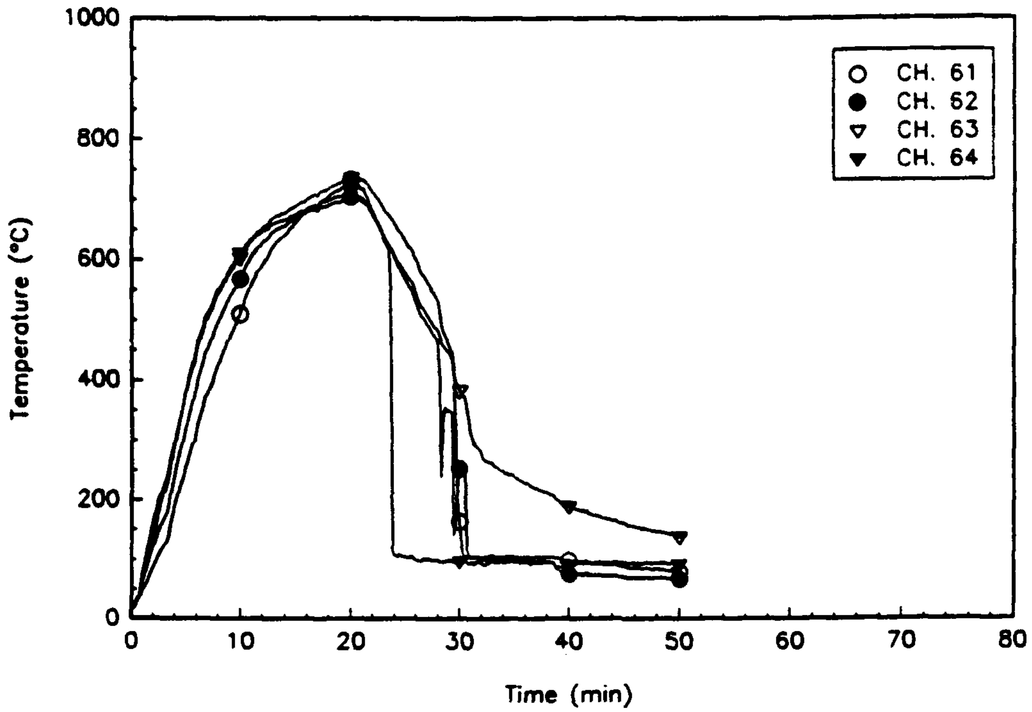

Fig. A120 – RICER 2 deck temperatures aft, COL_14

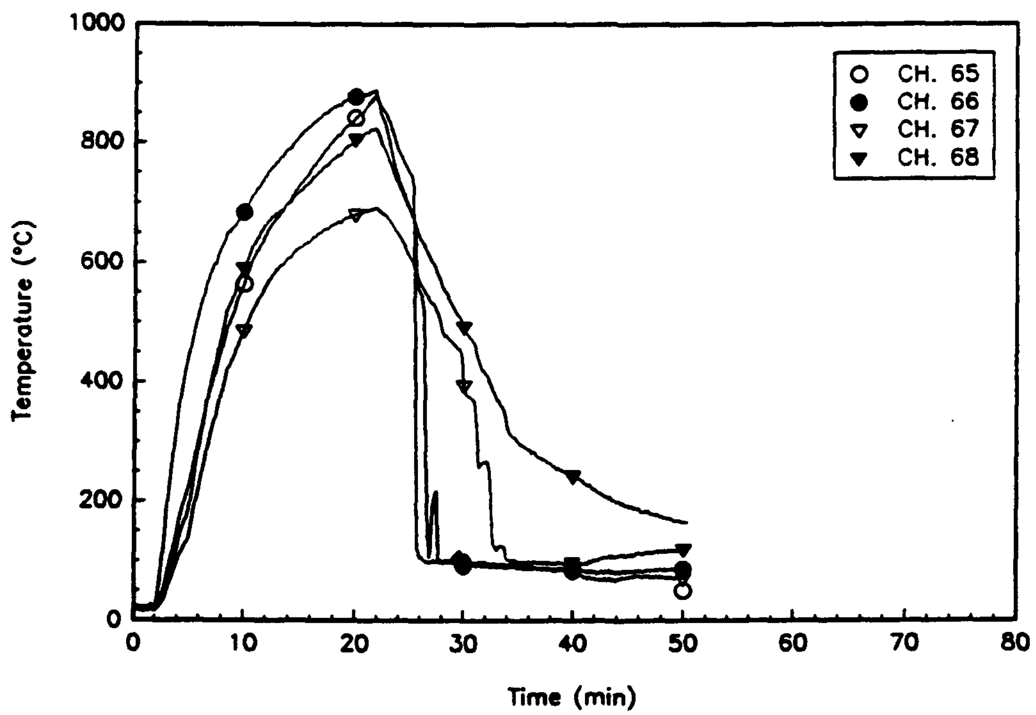

Fig. A121 – RICER 2 deck temperatures forward, COL_14

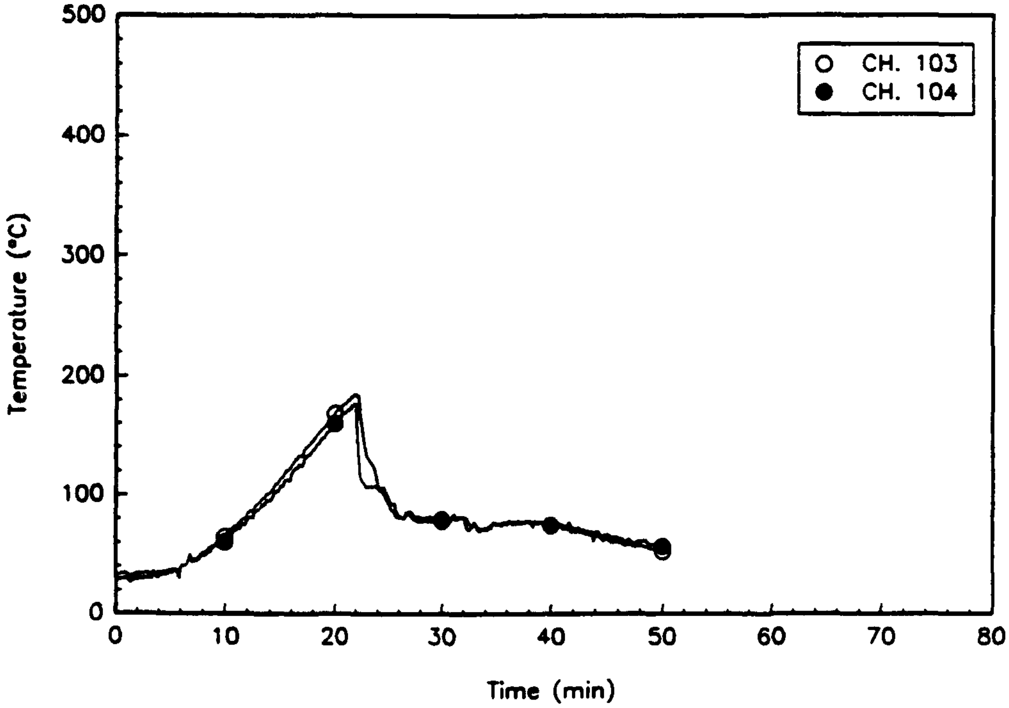

Fig. A122 – CIC deck temperatures, COL_14

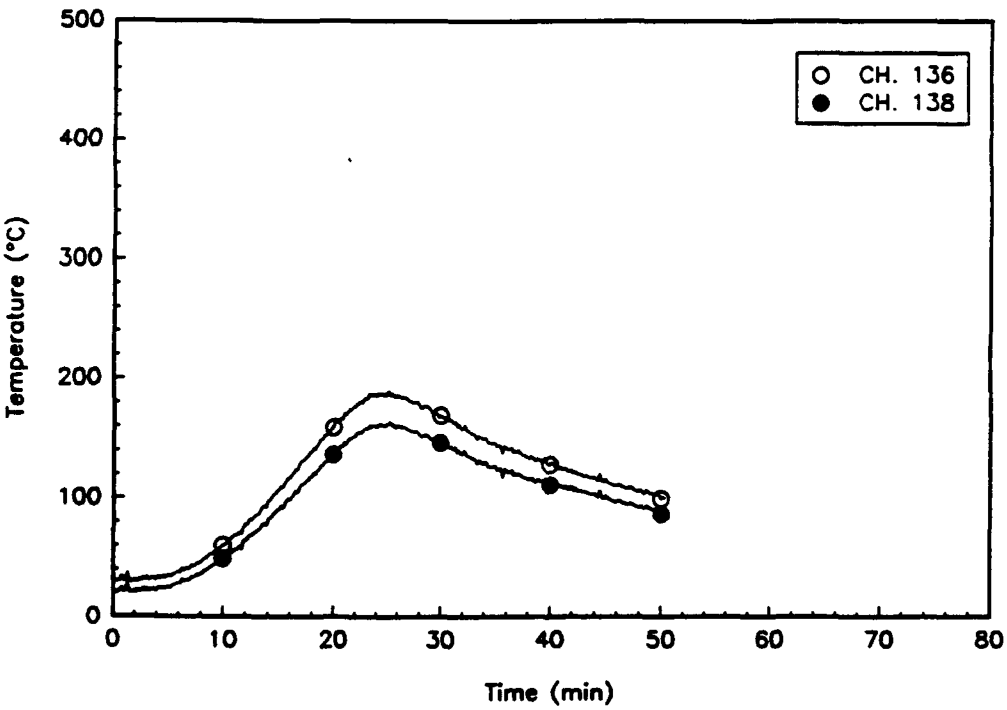

Fig. A123 – FR 88 bulkhead temperatures (RICER 2 side), COL_14

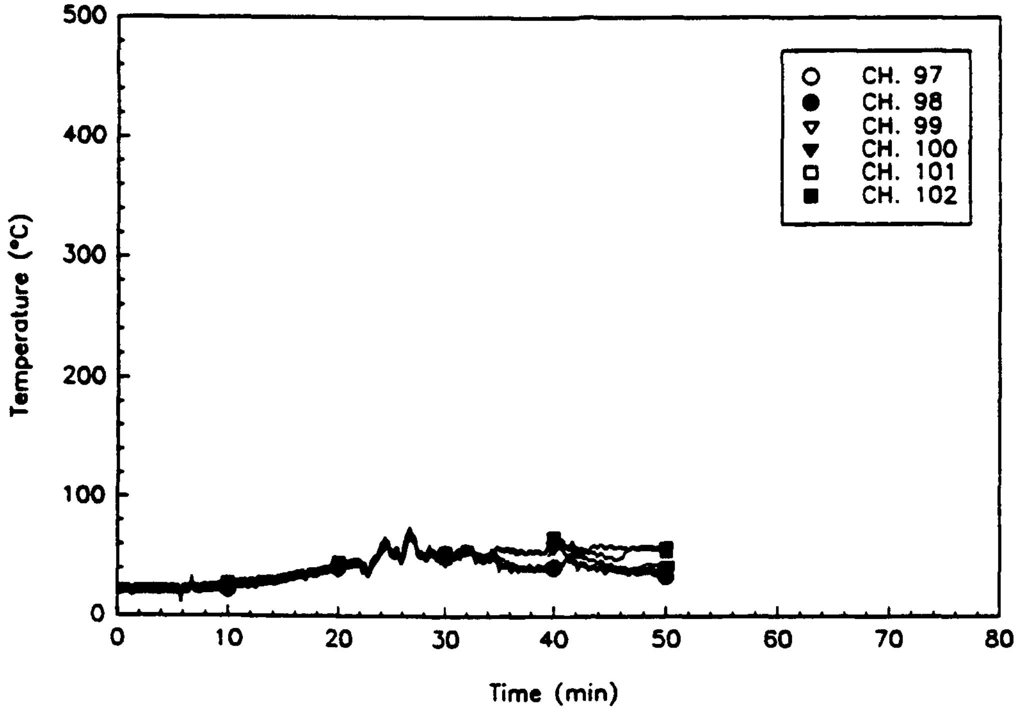

Fig. A124 – CIC air temperature aft, COL_14

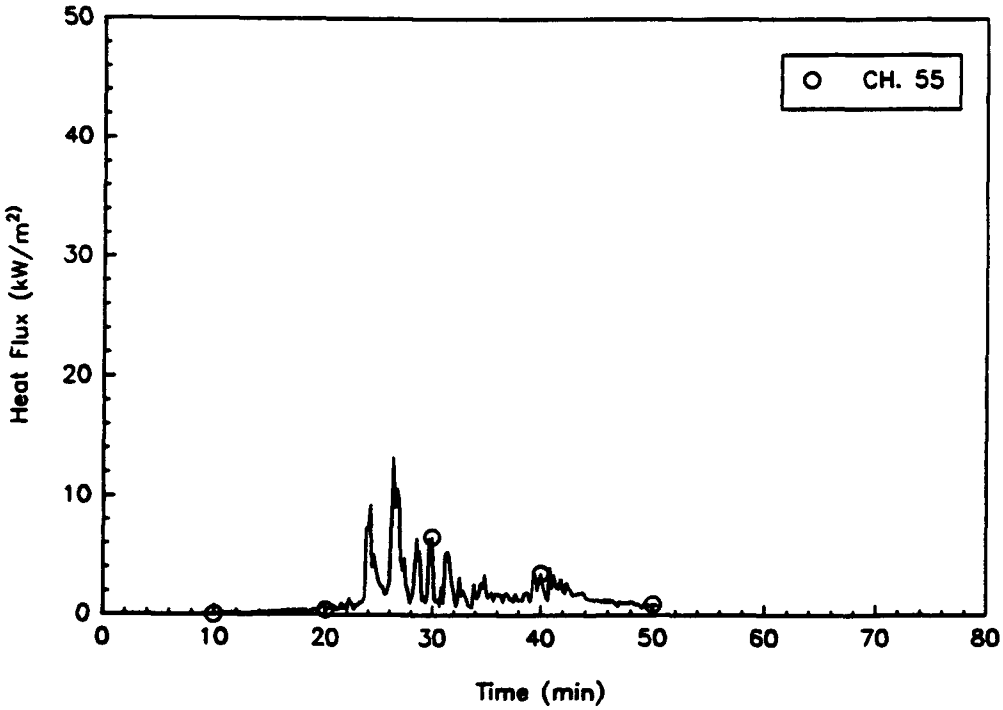

Fig. A125 – Total heat flux at CIC overhead, COL_14

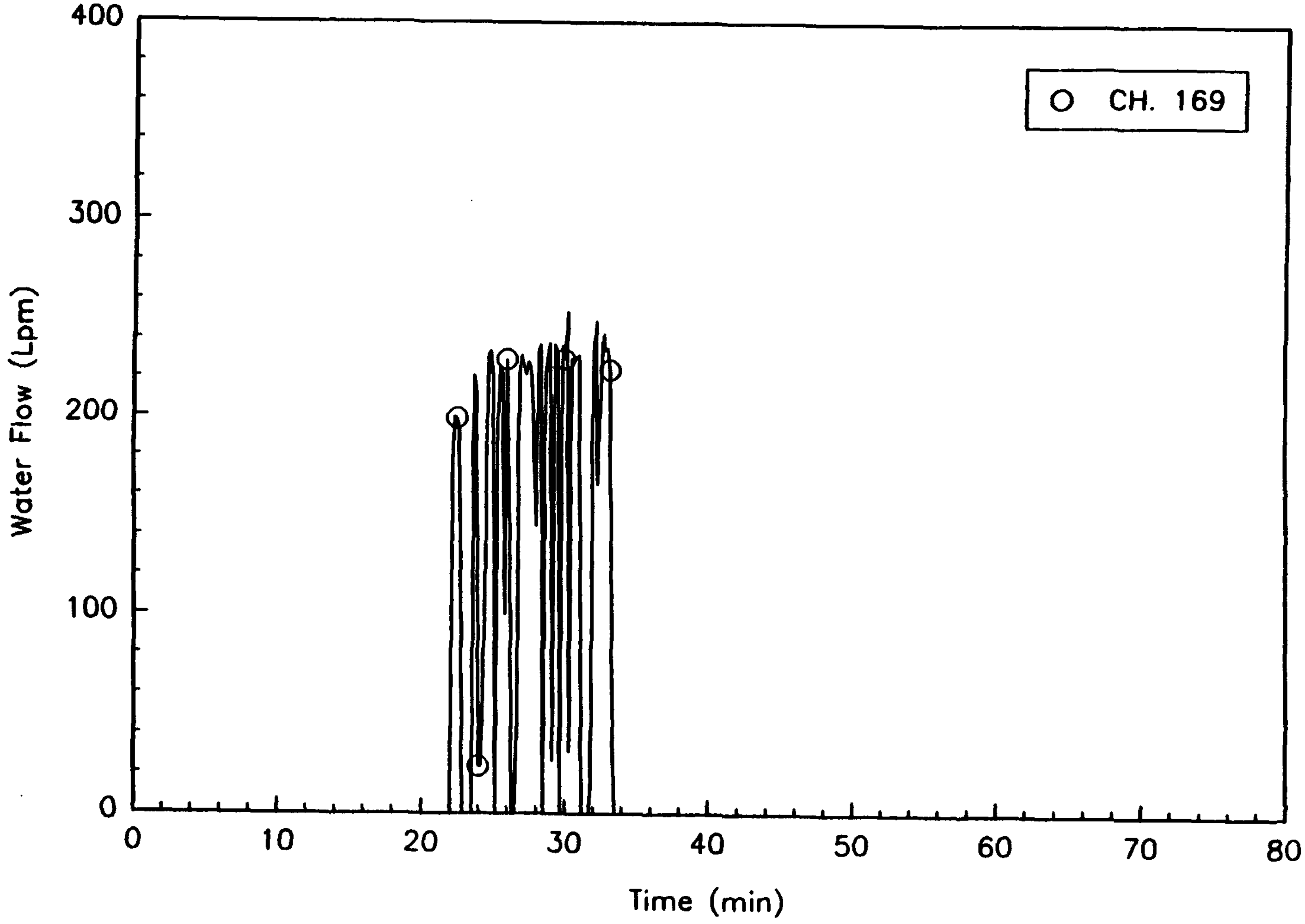

Fig. A126 — Water flow from cooling handline, COL_14

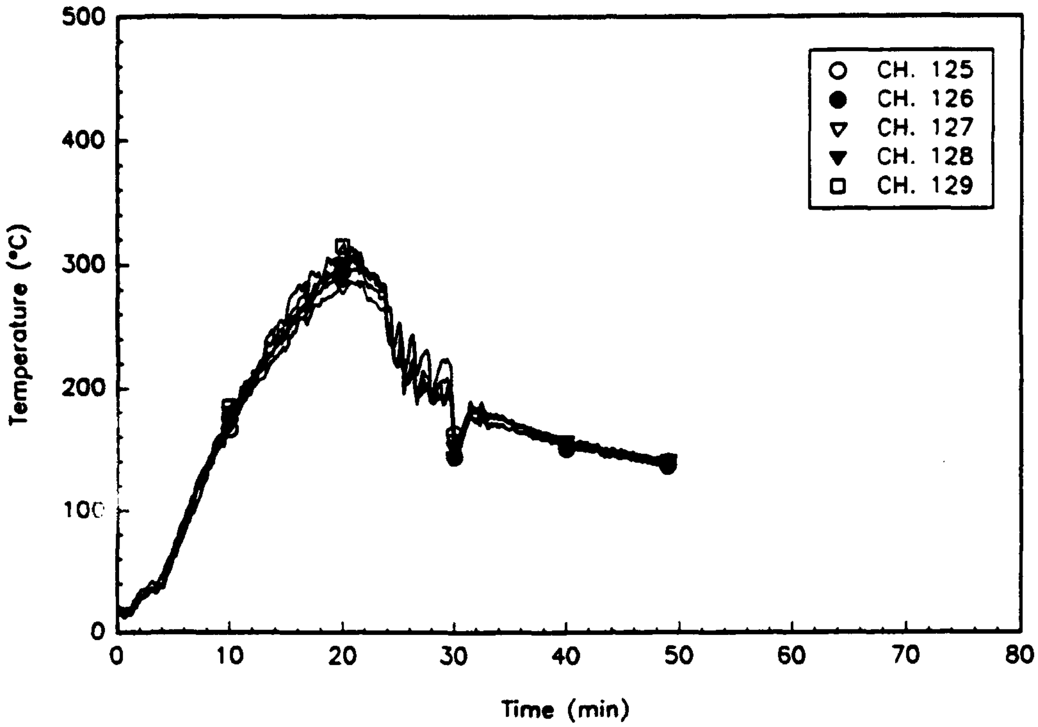

Fig. A127 — RICER 2 air temperatures forward, COL_15

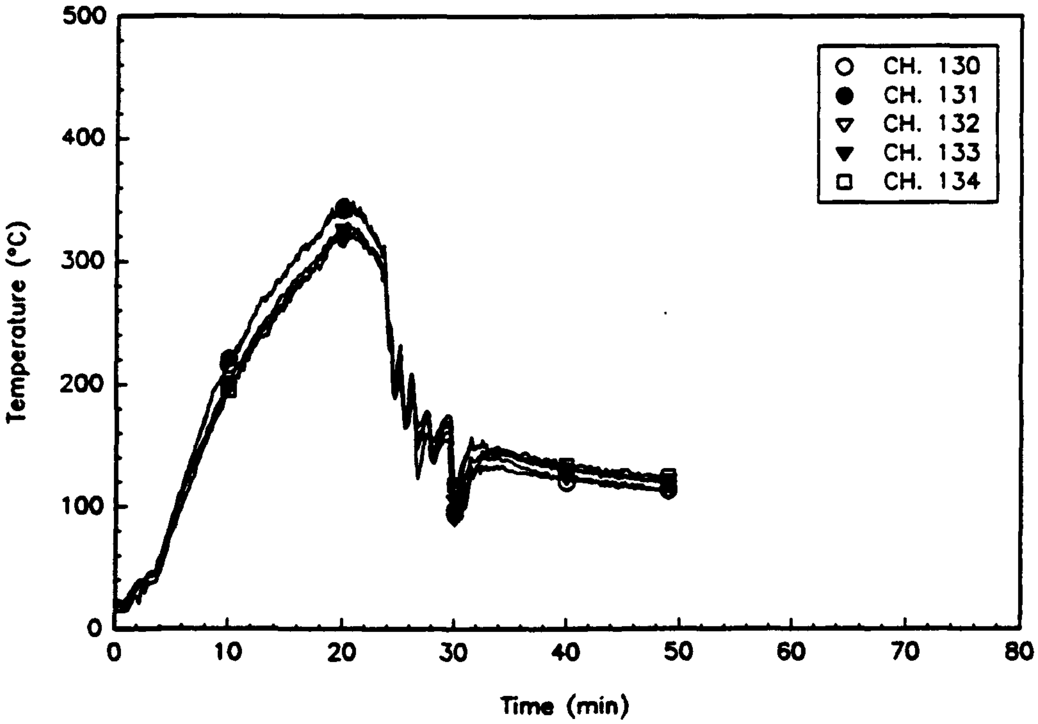

Fig. A128 — RICER 2 air temperatures aft, COL_15

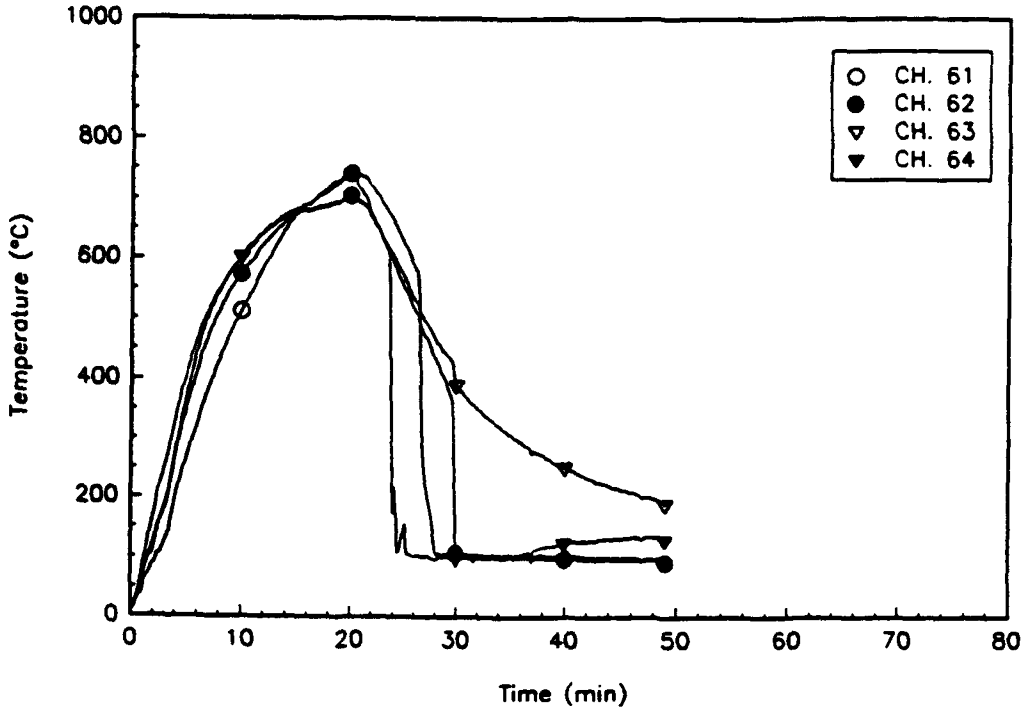

Fig. A129 – RICER 2 deck temperatures aft, COL_15

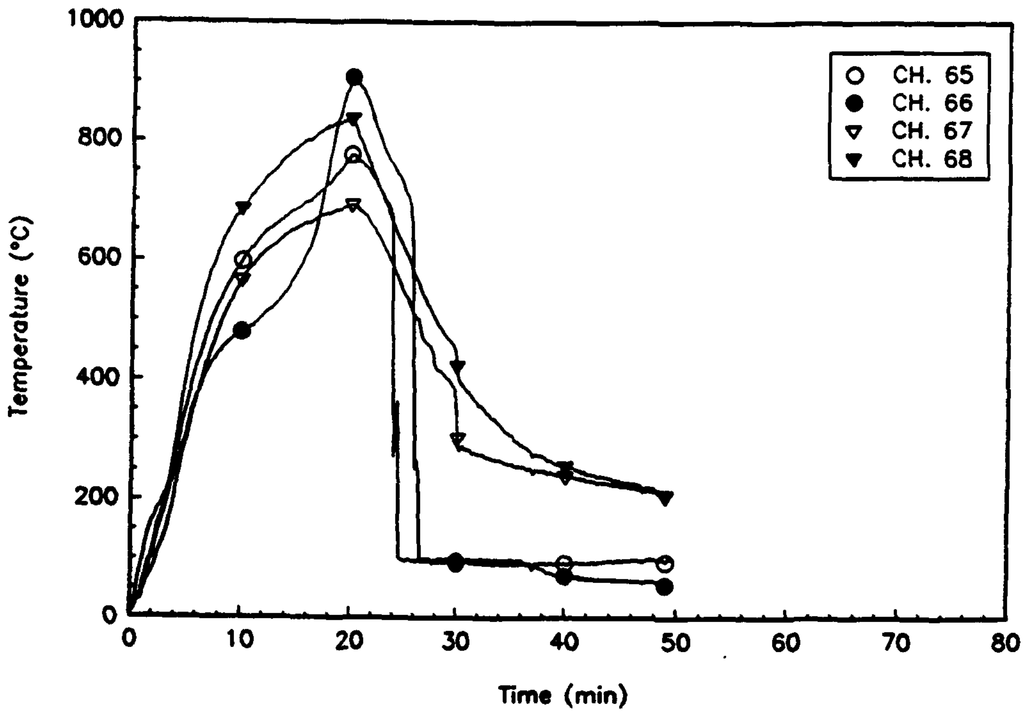

Fig. A130 – RICER 2 deck temperatures forward, COL_15

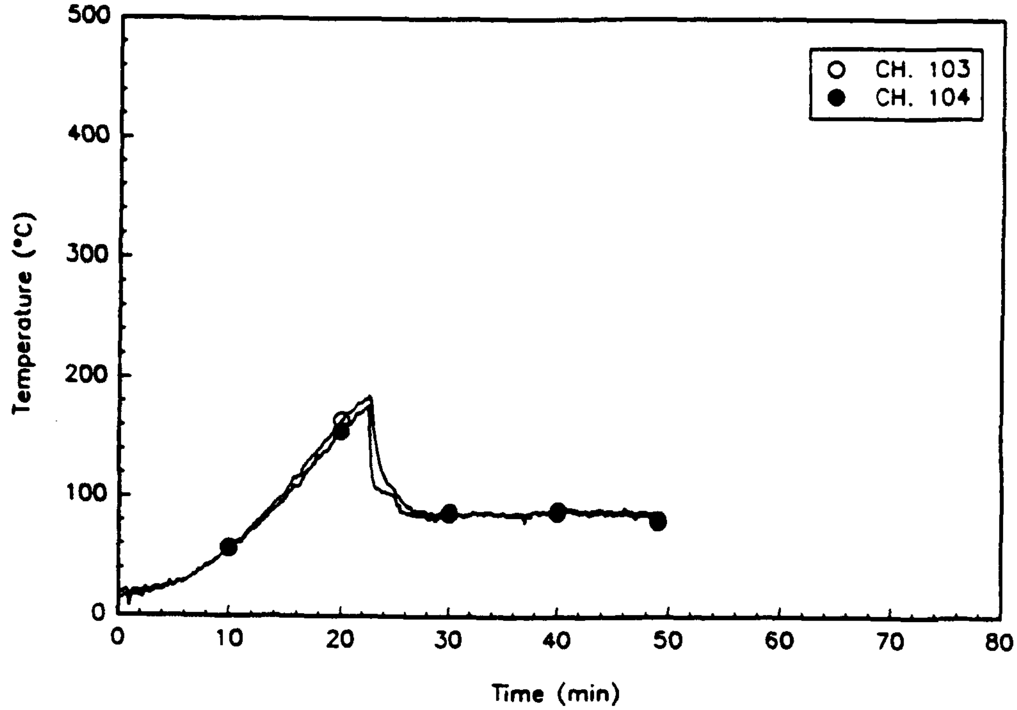

Fig. A131 – CIC deck temperatures, COL_15

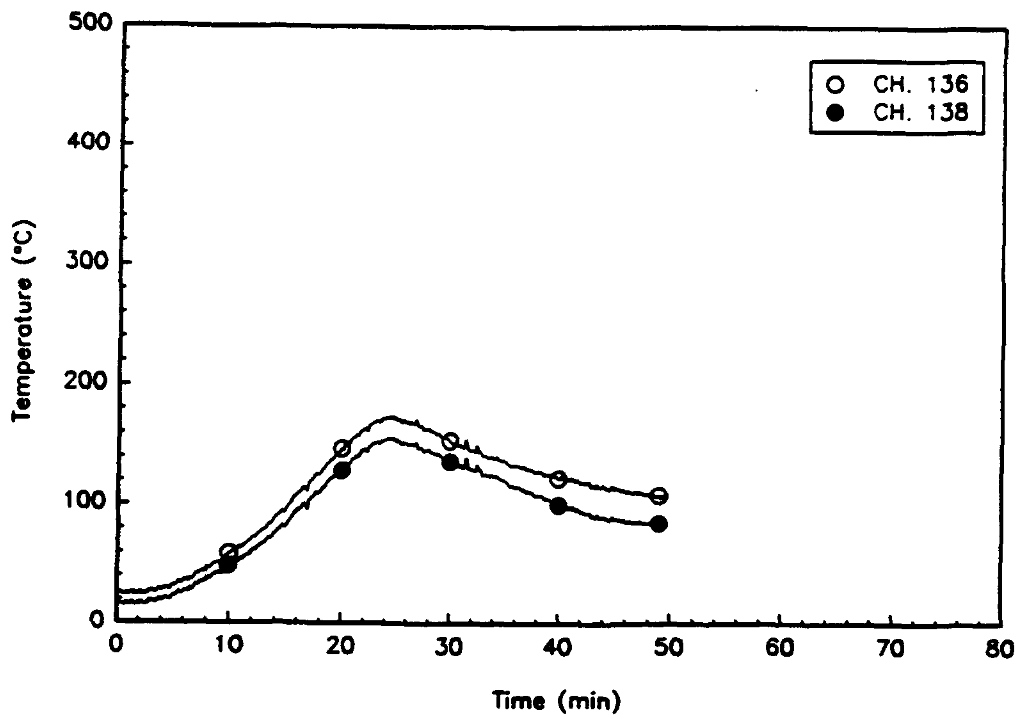

Fig. A132 – FR 88 bulkhead temperatures (RICER 2 side), COL_15

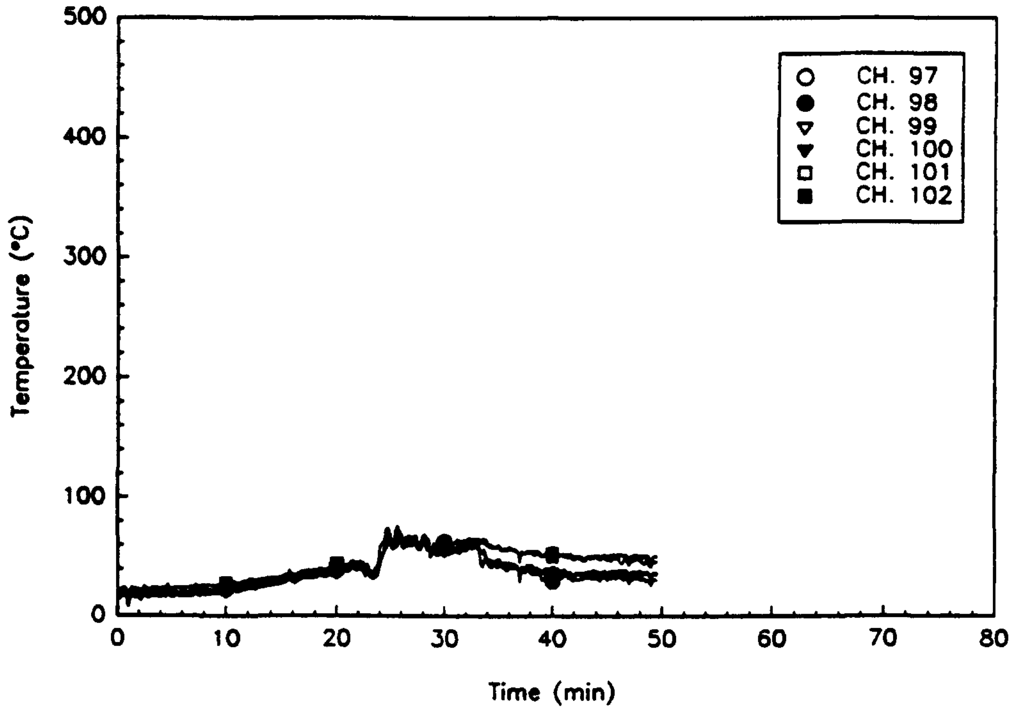

Fig. A133 – CIC air temperature aft, COL_15

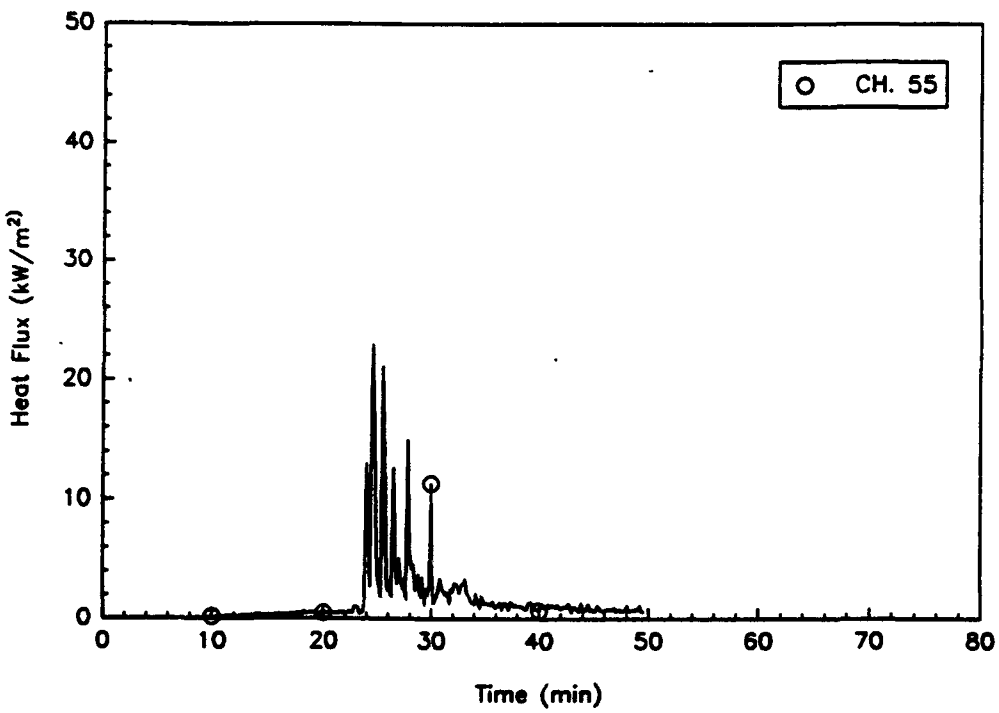

Fig. A134 – Total heat flux at CIC overhead, COL_15

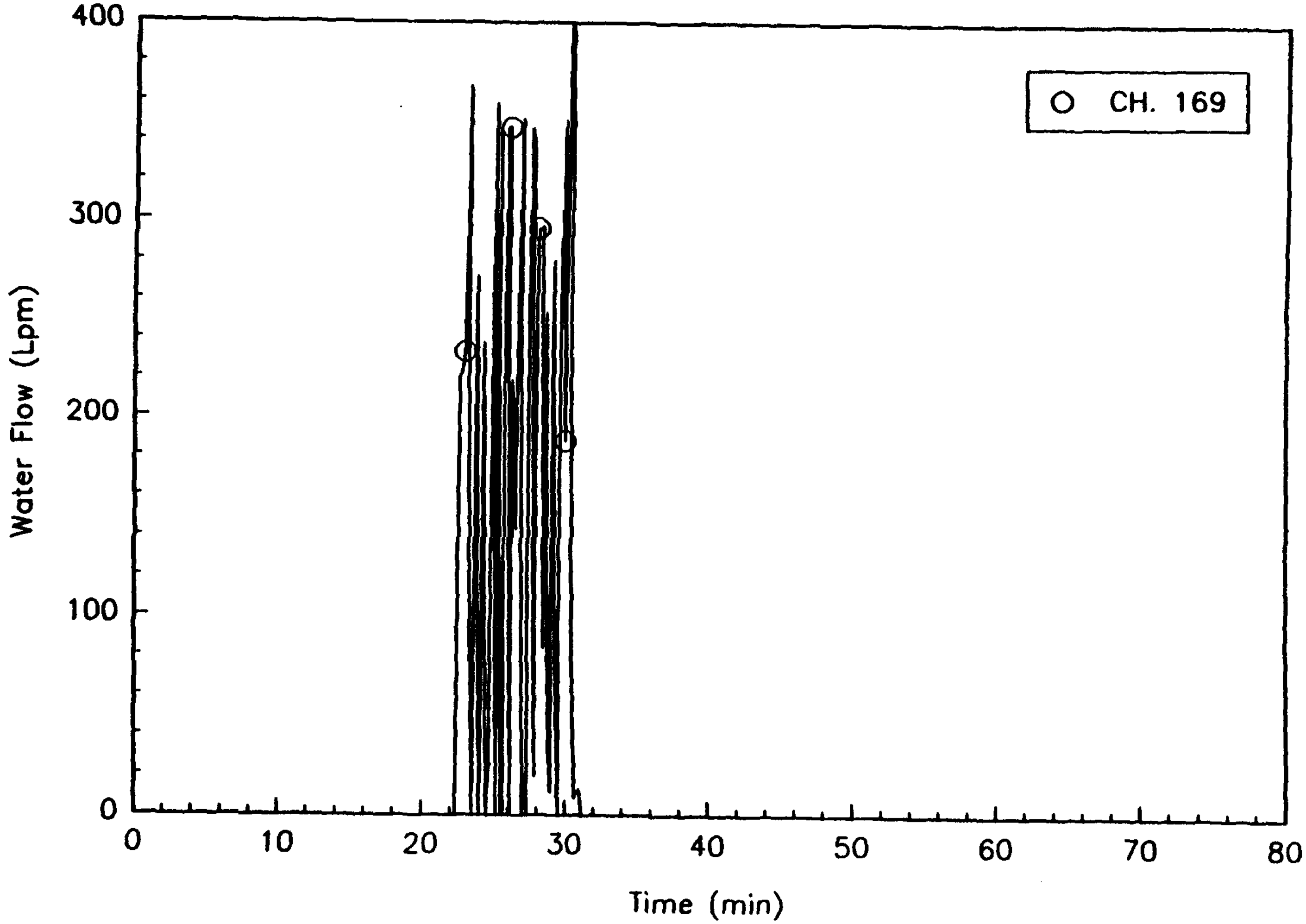

Fig. A135 — Water flow from cooling handline, COL_15

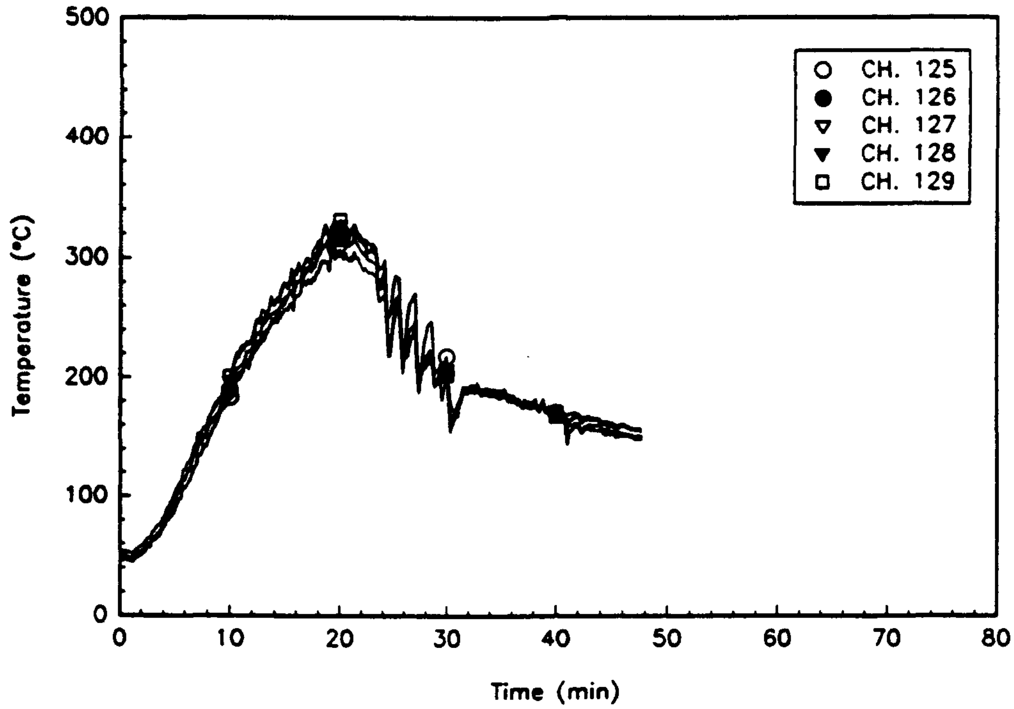

Fig. A136 — RICER 2 air temperatures forward, COL_16

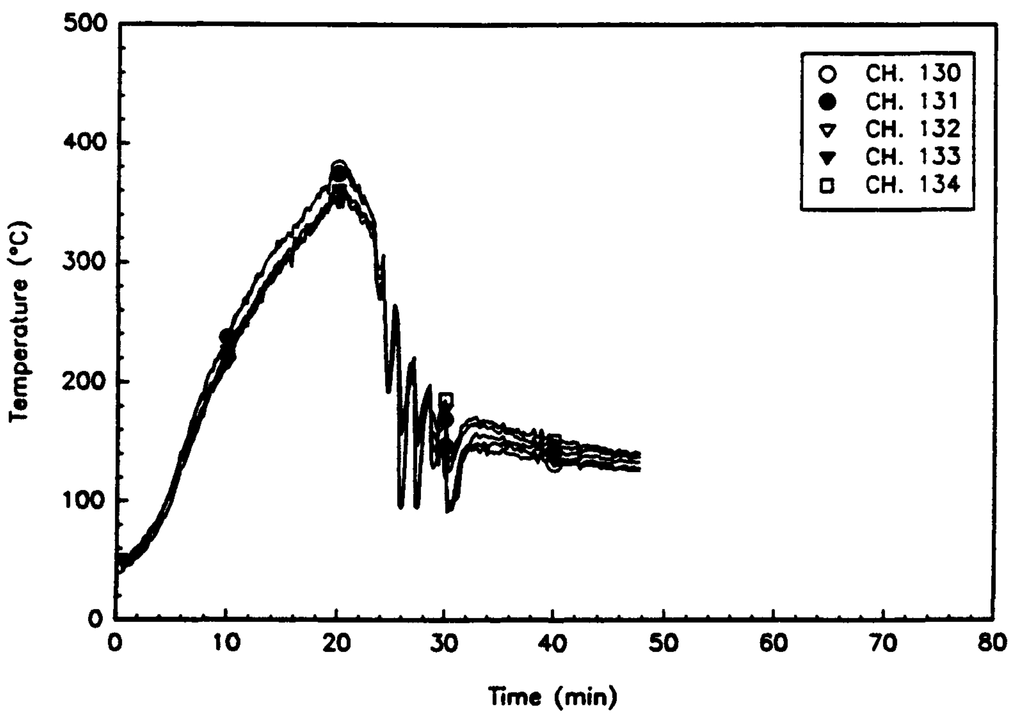

Fig. A137 — RICER 2 air temperatures aft, COL_16

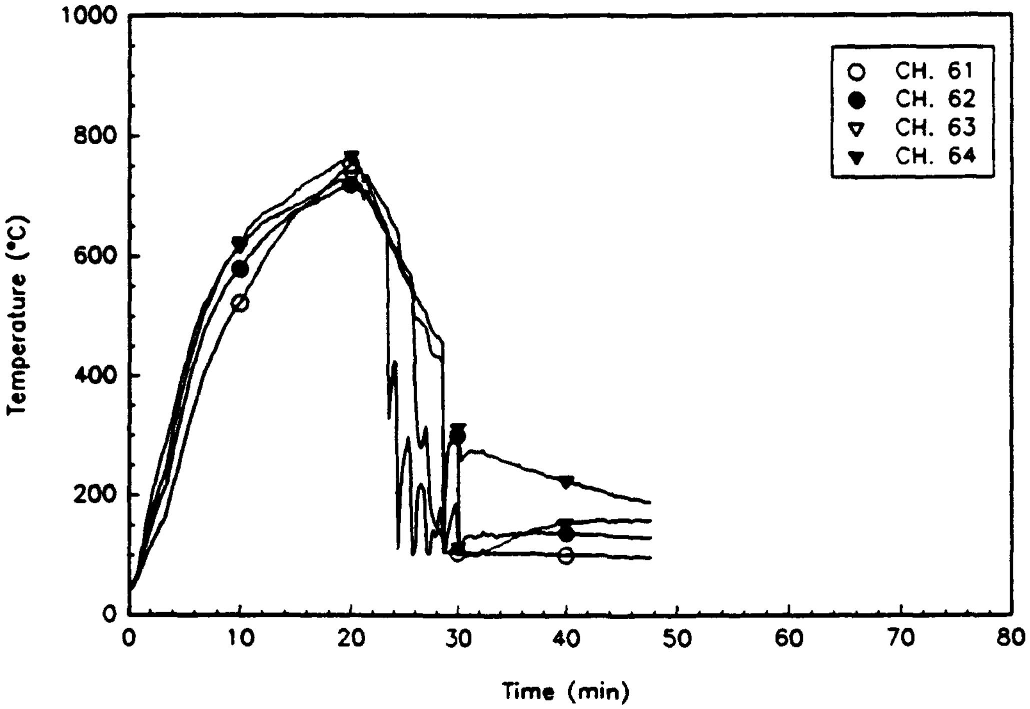

Fig. A138 — RICER 2 deck temperatures aft, COL_16

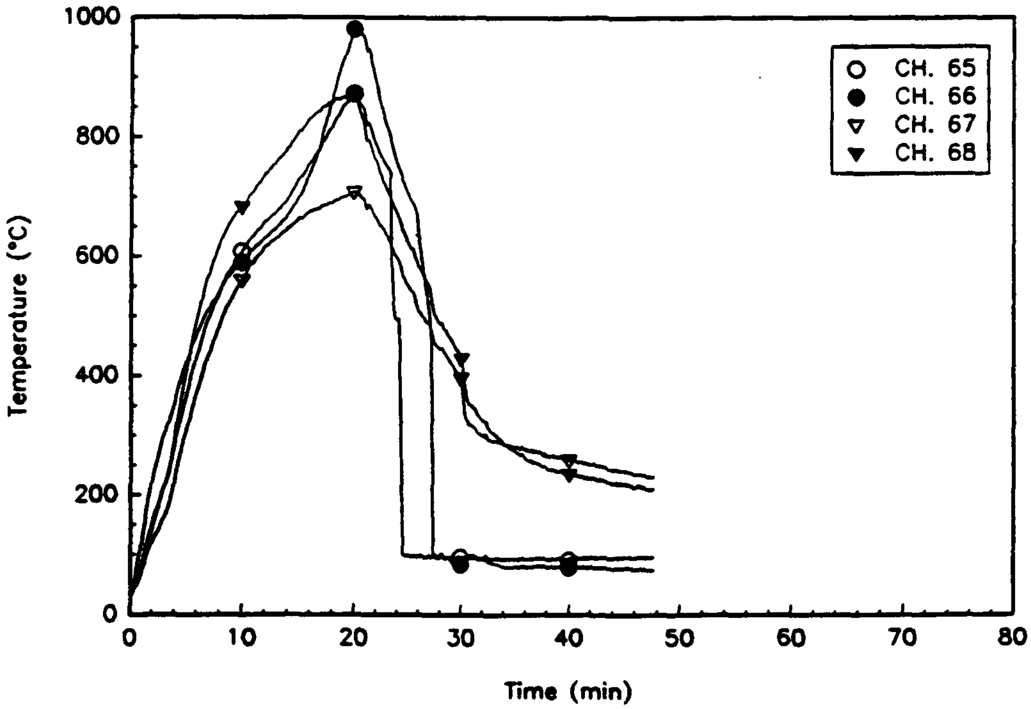

Fig. A139 — RICER 2 deck temperatures forward, COL_16

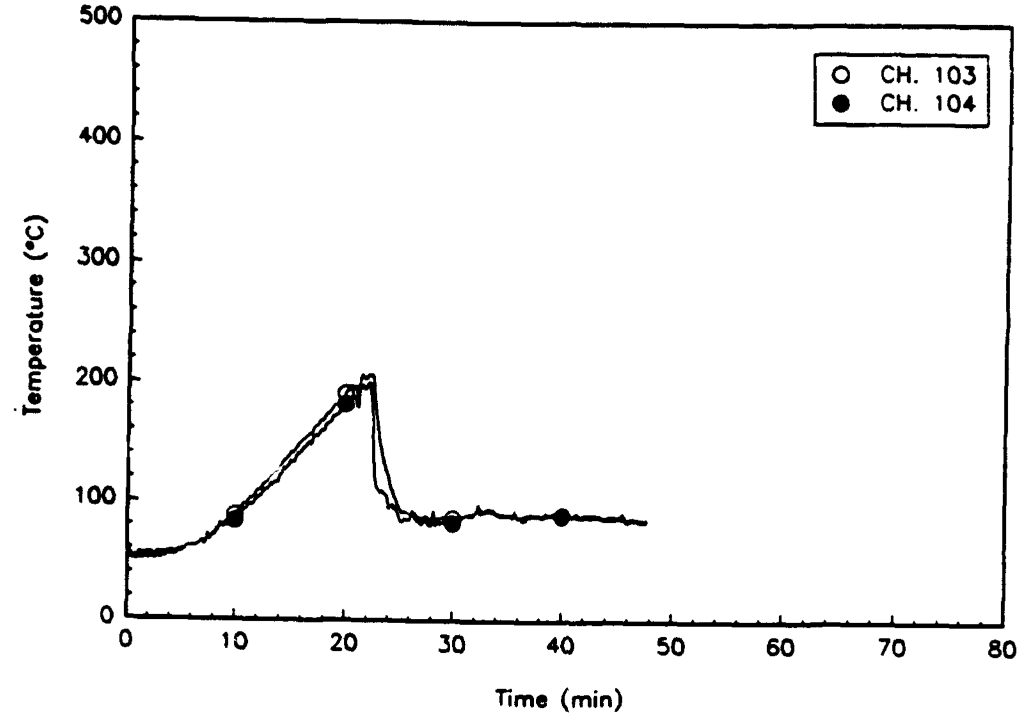

Fig. A140 – CIC deck temperatures, COL_16

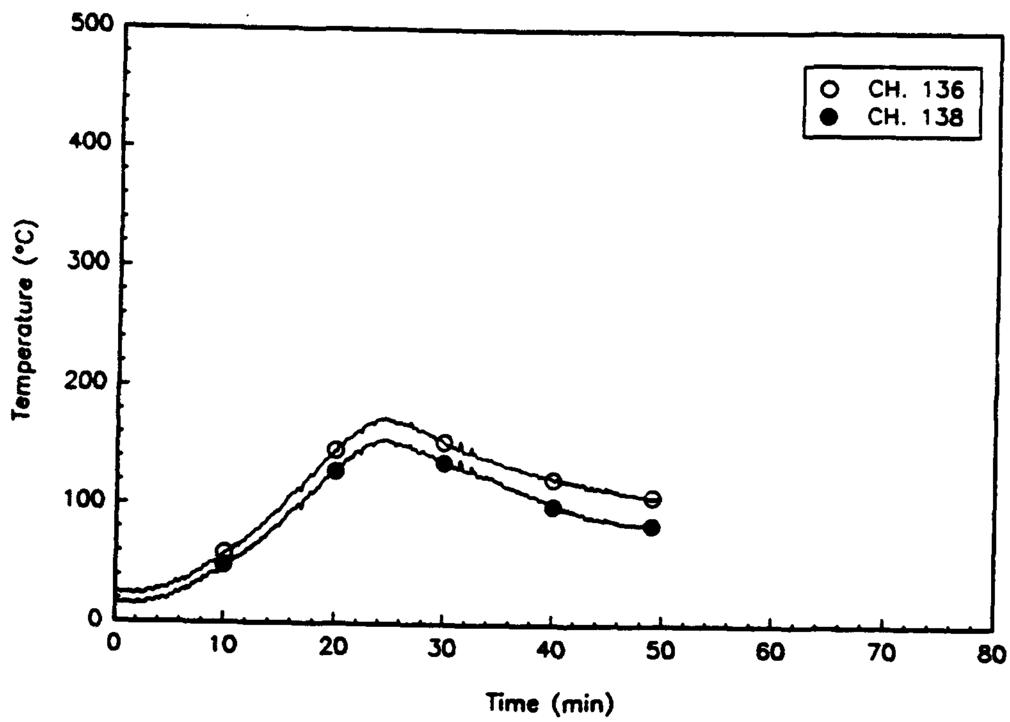

Fig. A141 – FR 88 bulkhead temperatures (RICER 2 side), COL_16

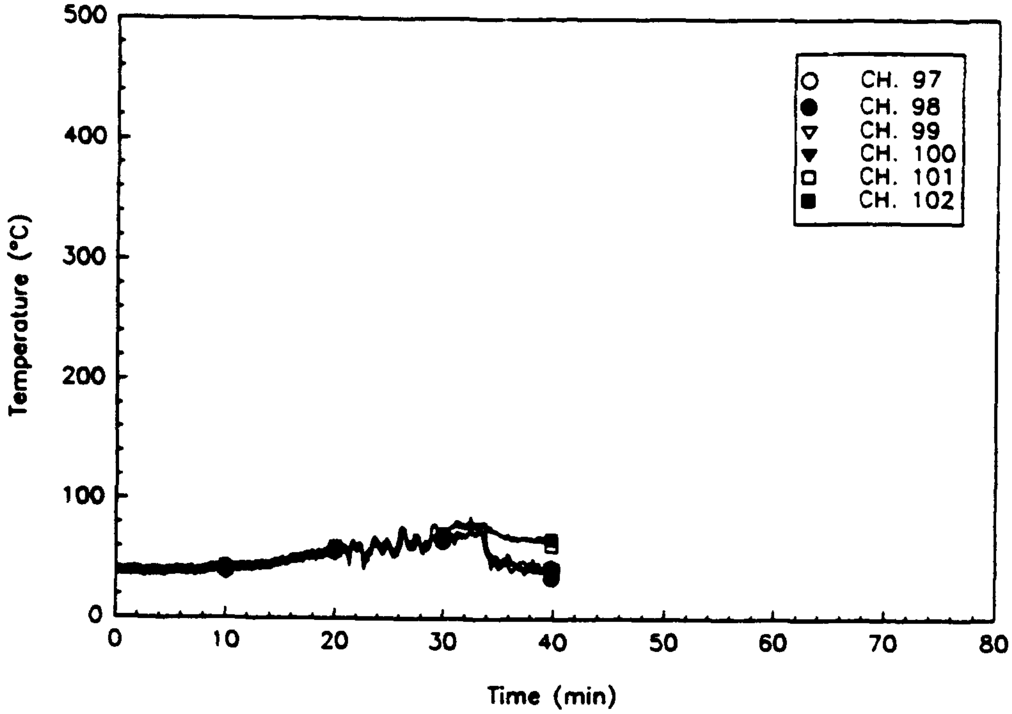

Fig. A142 – CIC air temperatures aft, COL_16

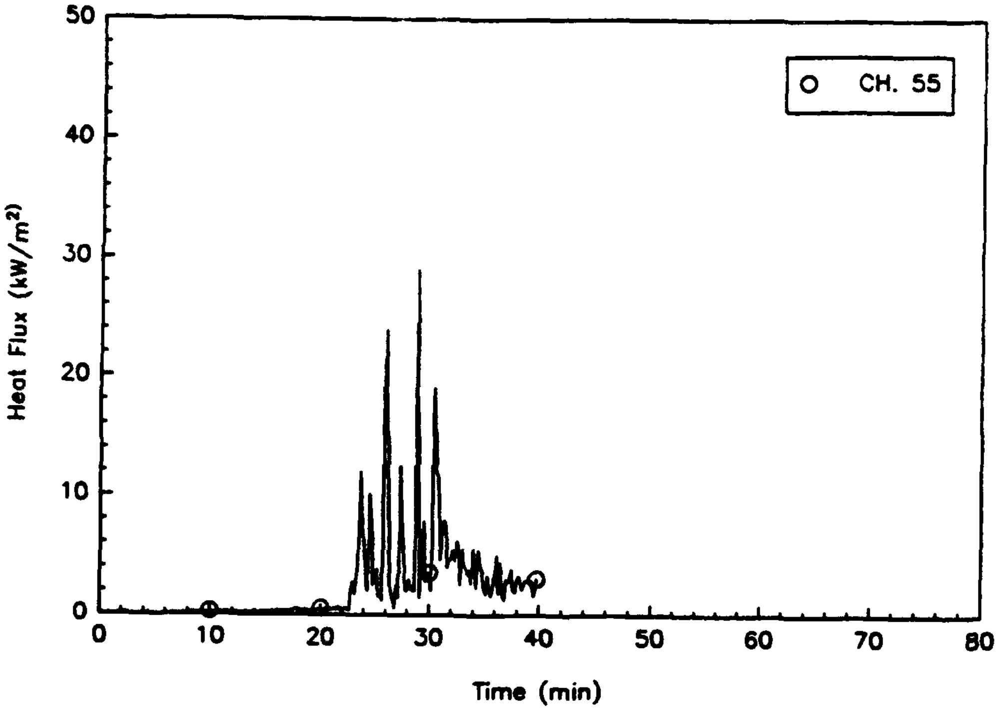

Fig. A143 – Total heat flux at CIC overhead, COL_16

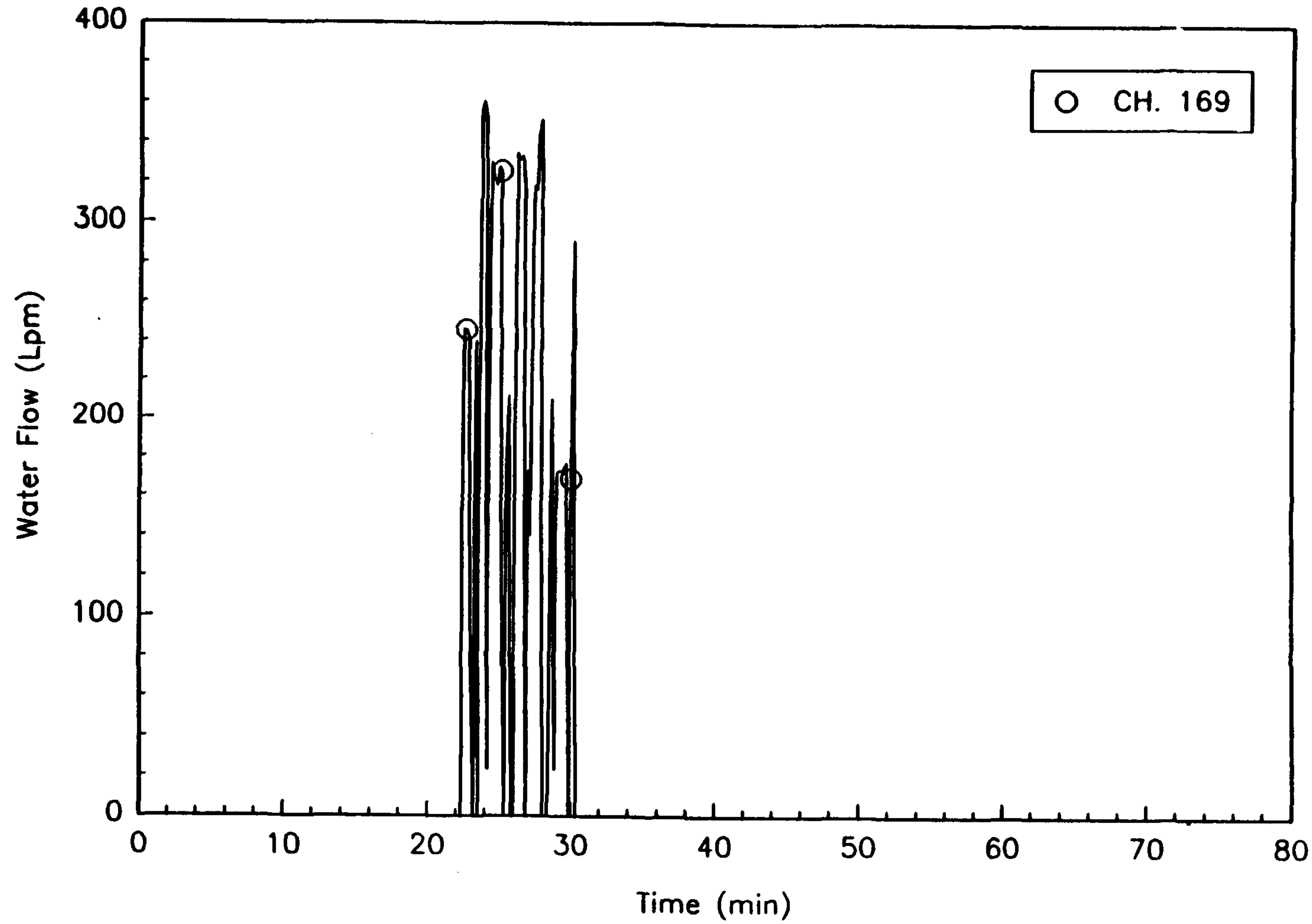

Fig. A144 – Water flow from cooling handline, COL_16

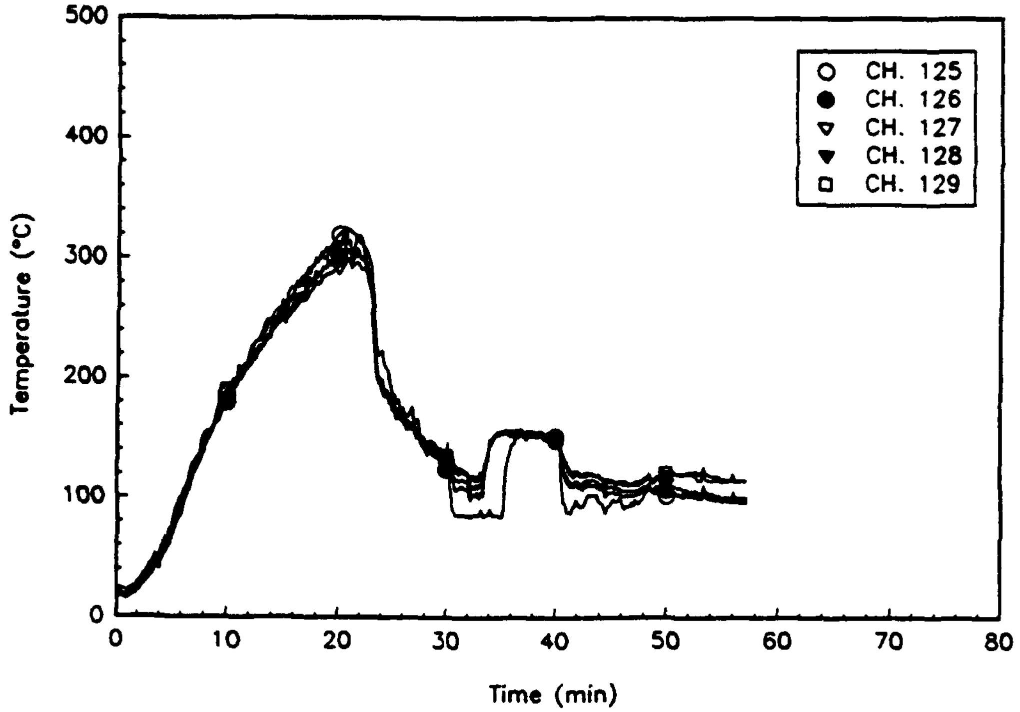

Fig. A145— RICER 2 air temperature forward, INS_4

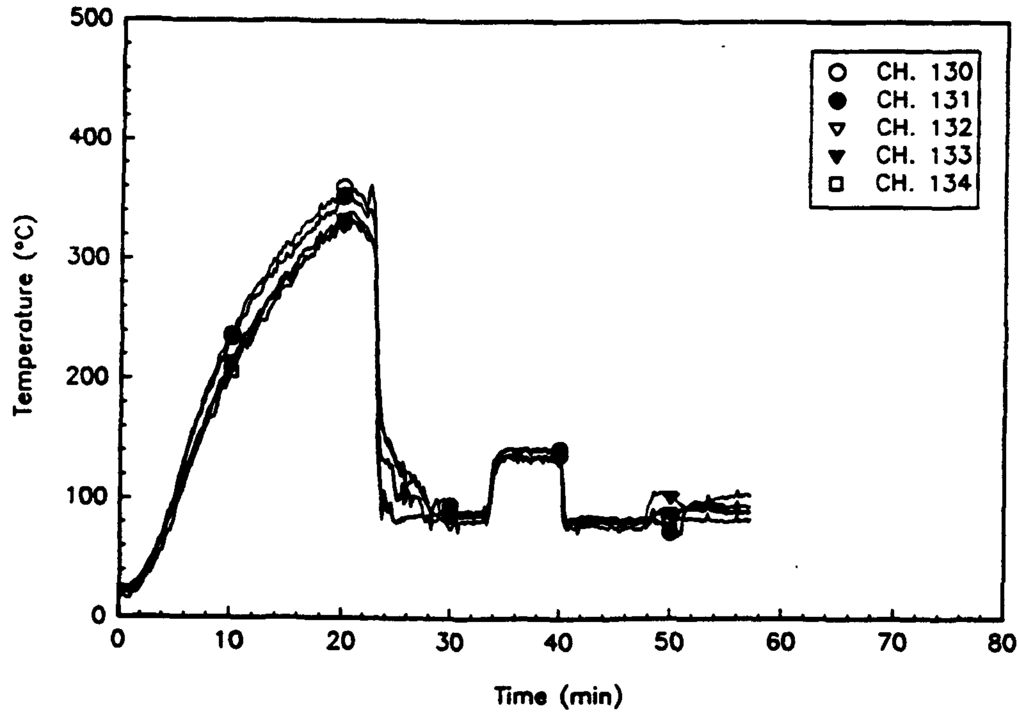

Fig. A146 — RICER 2 air temperature aft, INS_4

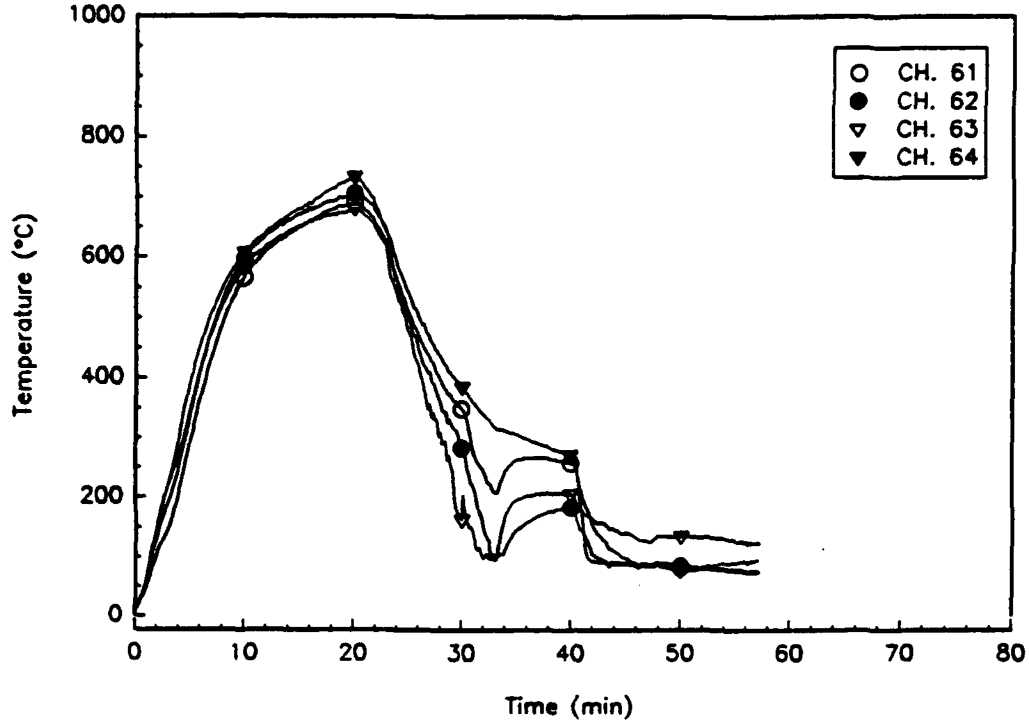

Fig. A147 — RICER 2 deck temperatures aft, INS_4

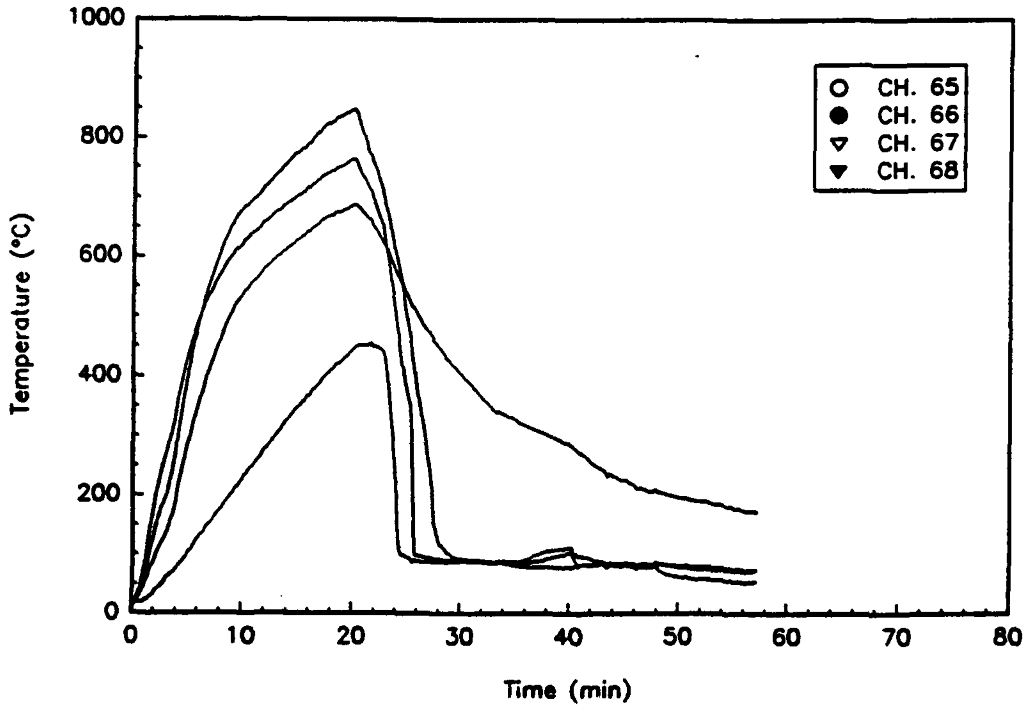

Fig. A148 — RICER 2 deck temperatures forward, INS_4

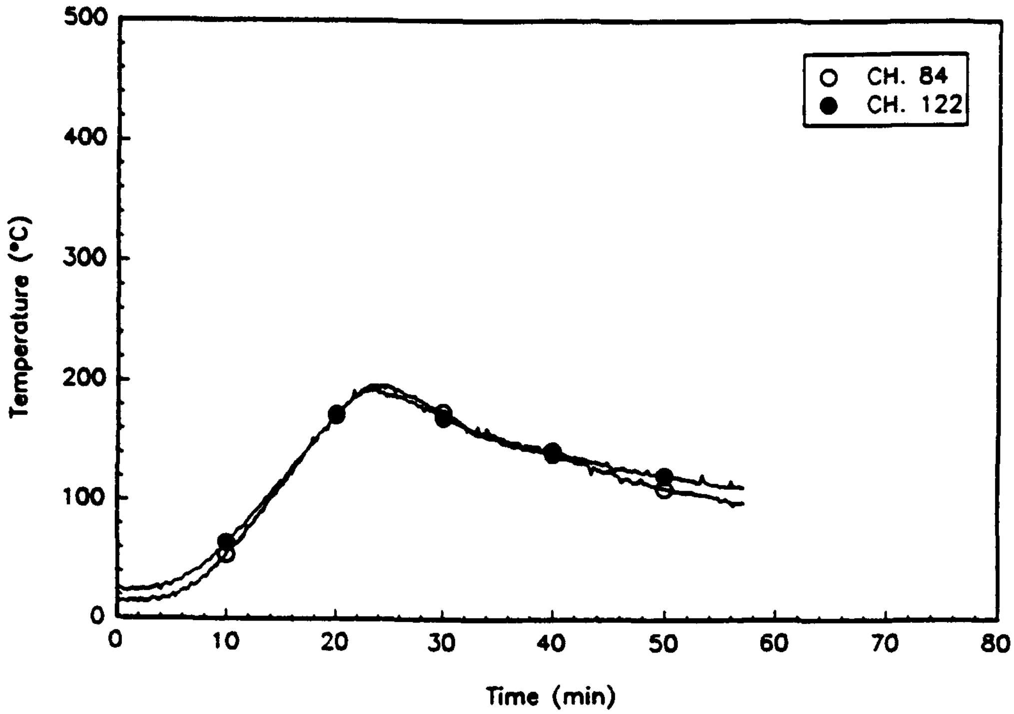

Fig. A149 – FR 81 bulkhead temperatures forward, INS_4

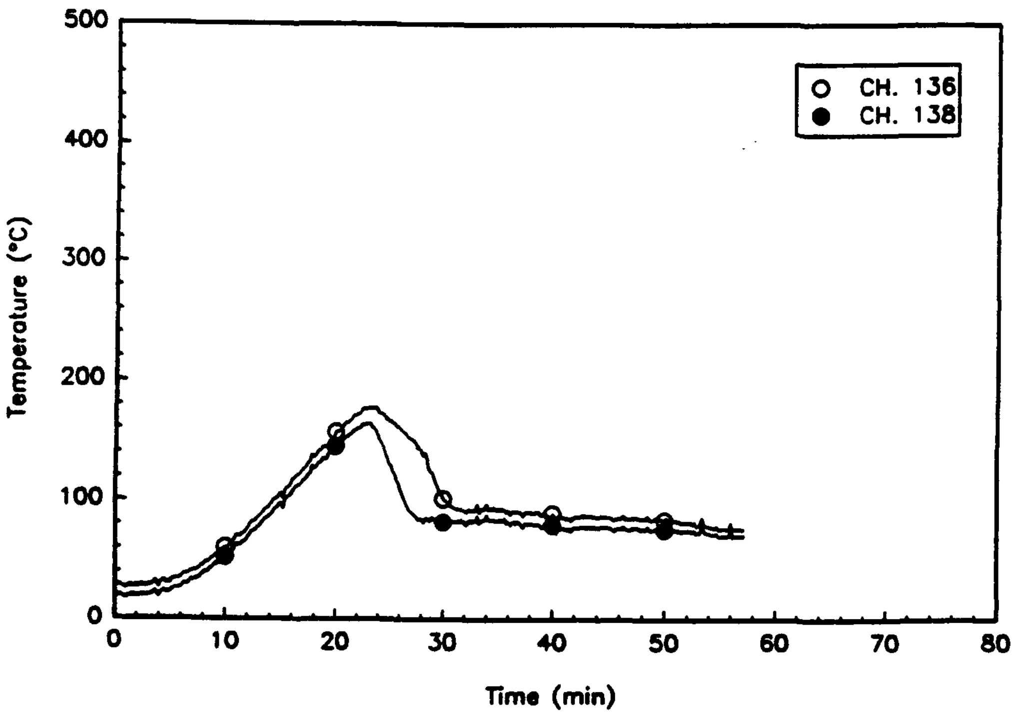

Fig. A150 – FR 88 bulkhead temperatures (RICER 2 side), INS_4

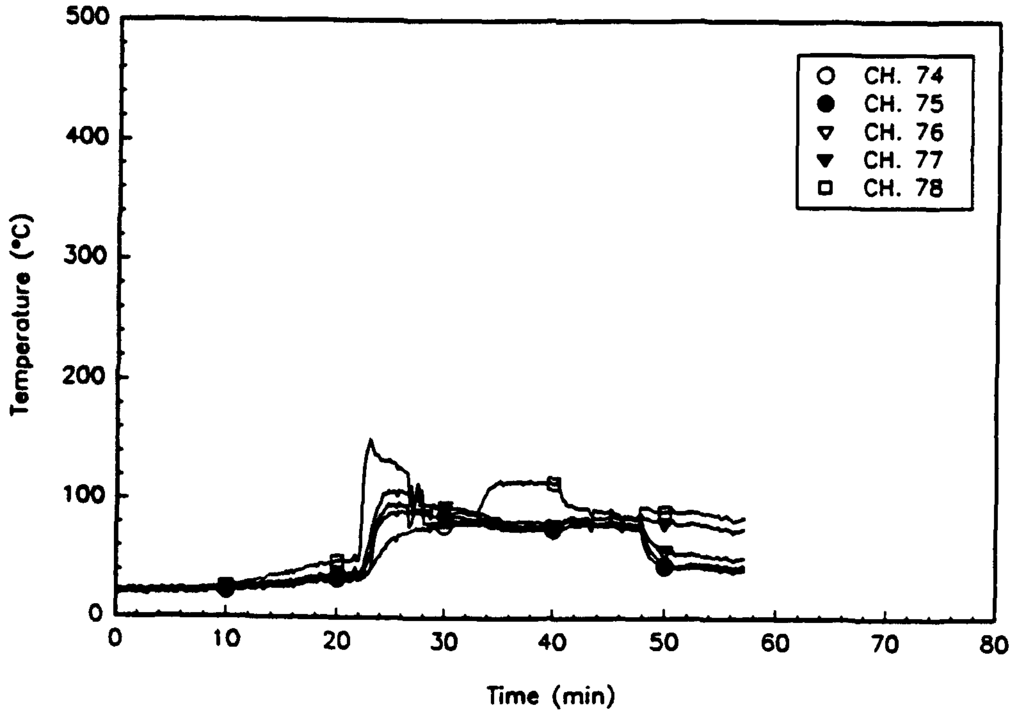

Fig. A151 – RICER 1 air temperatures, INS_4

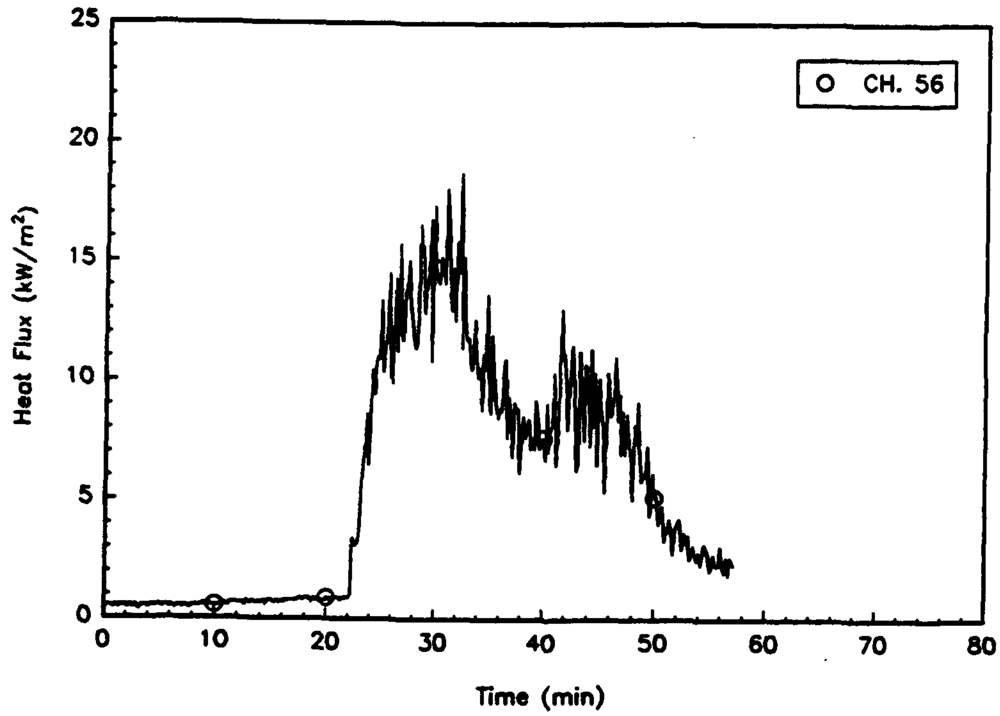

Fig. A152 – Total heat flux at RICER 1 overhead, INS_4

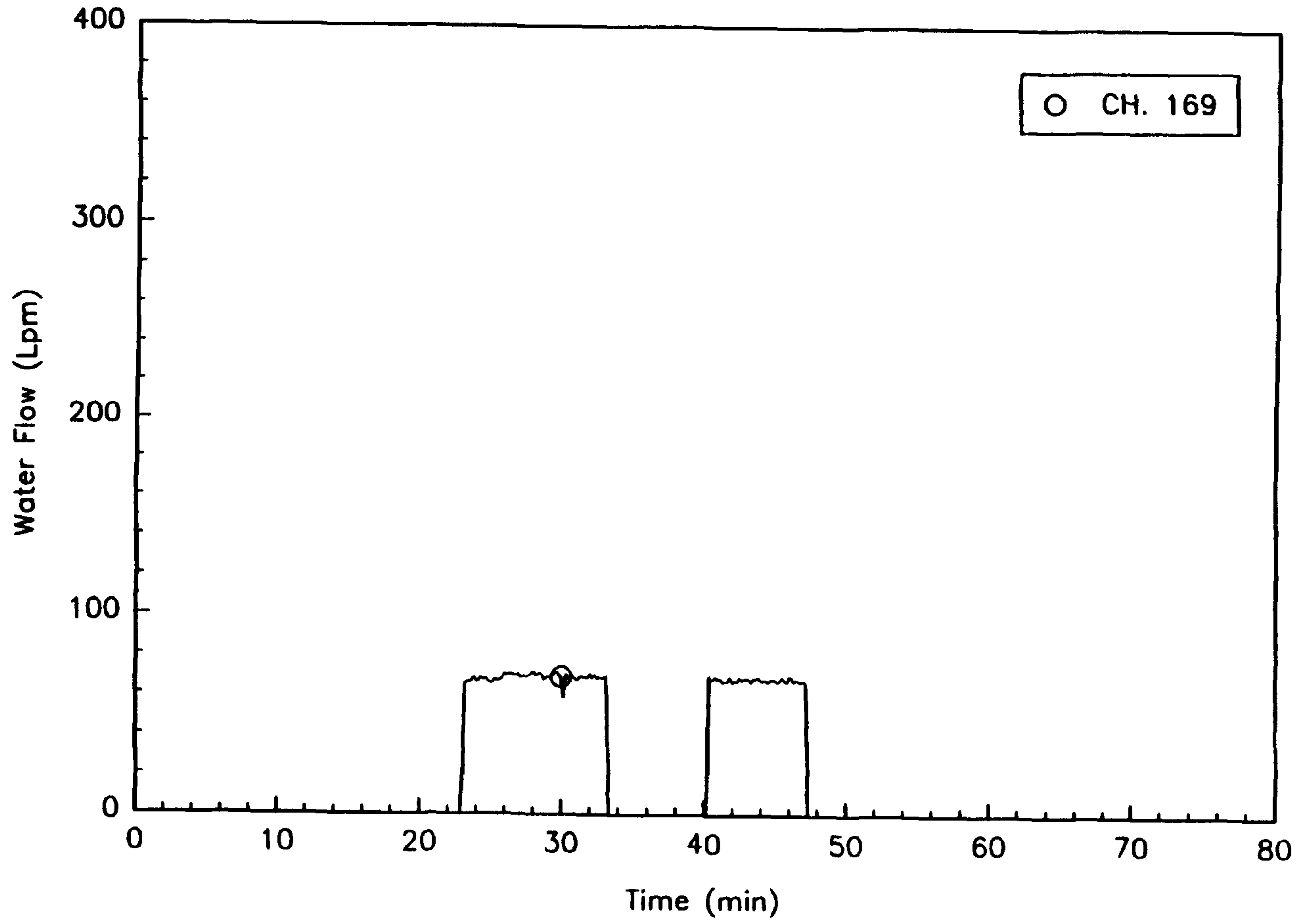

Fig A153 — Water flow from cooling handline, INS_4

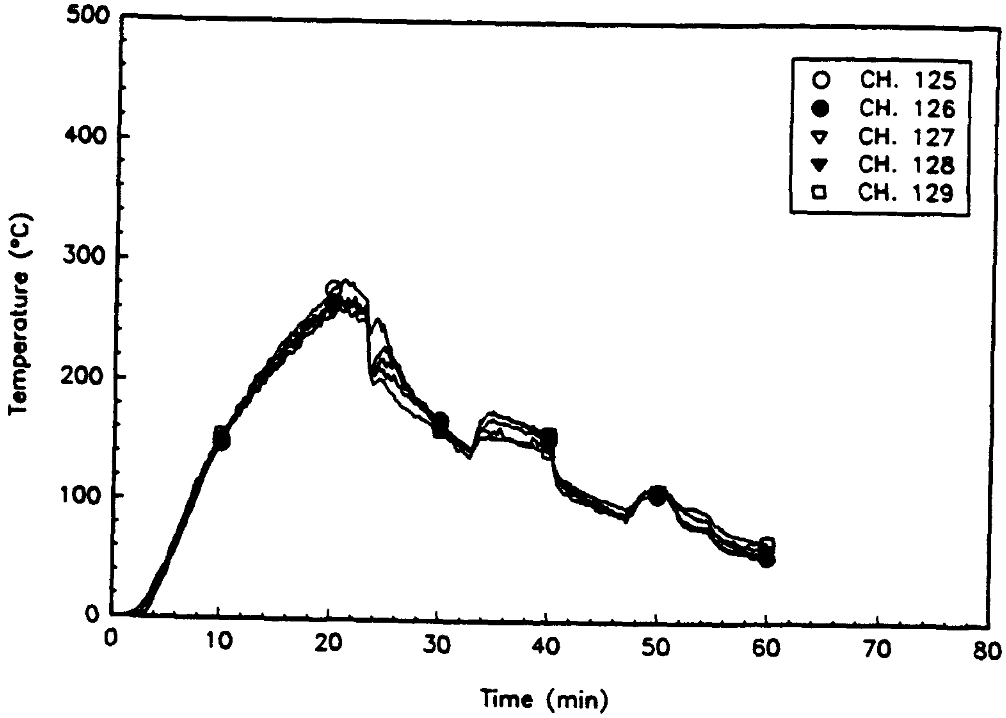

Fig. A154 – RICER 2 air temperature forward, INS_5A

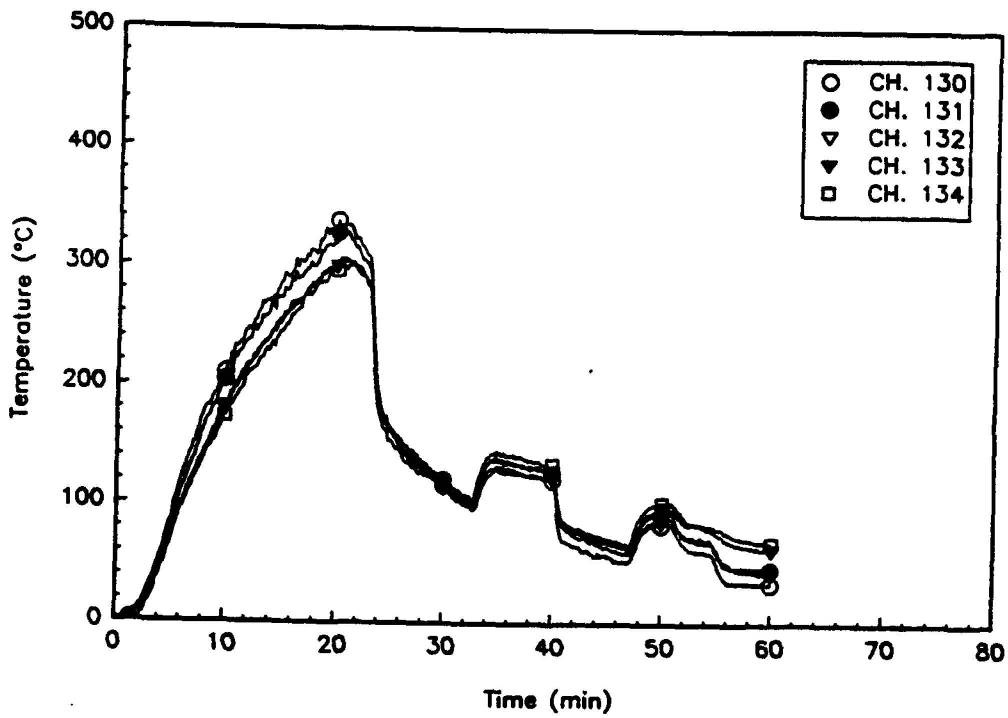

Fig. A155 – RICER 2 air temperature aft, INS_5A

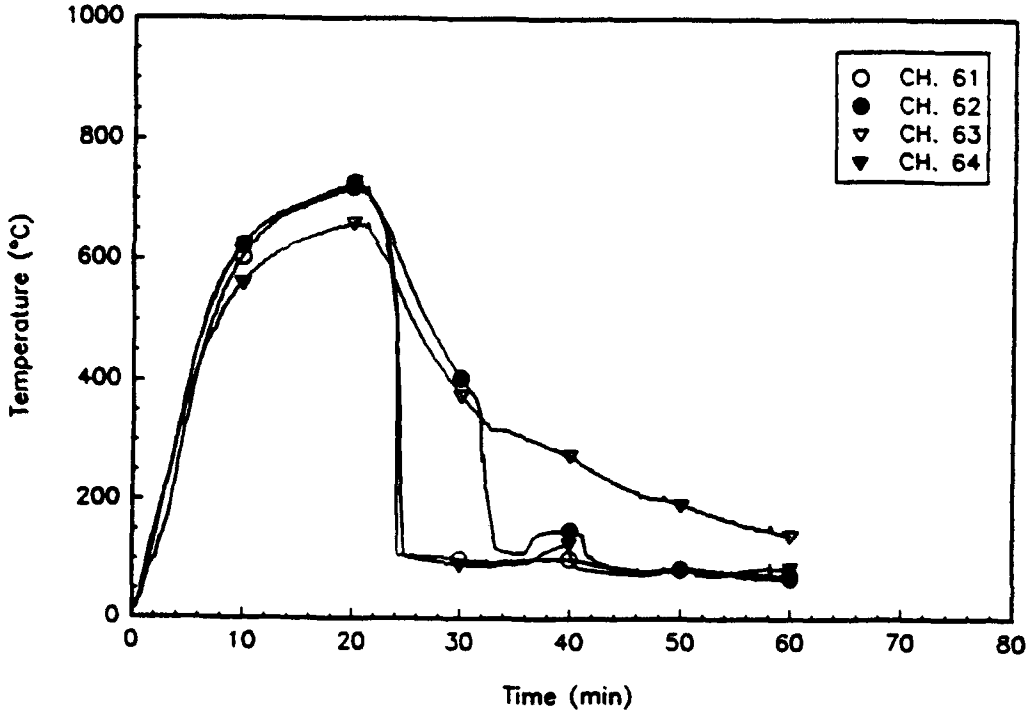

Fig. A156 – RICER 2 deck temperature aft, INS_5A

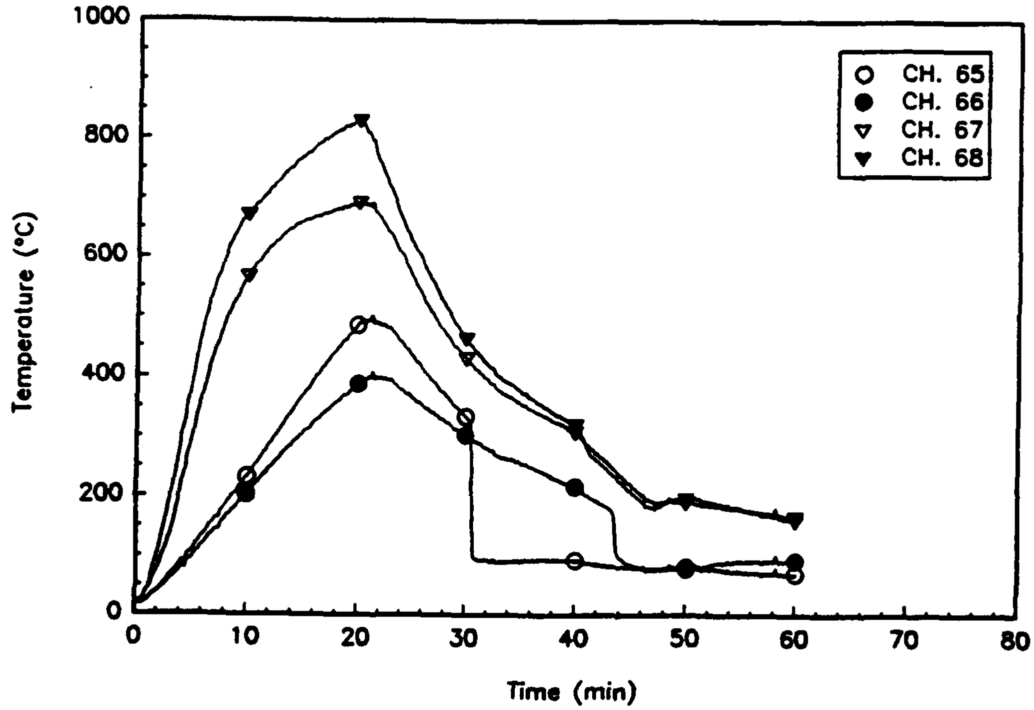

Fig. A157 – RICER 2 deck temperature forward, INS_5A

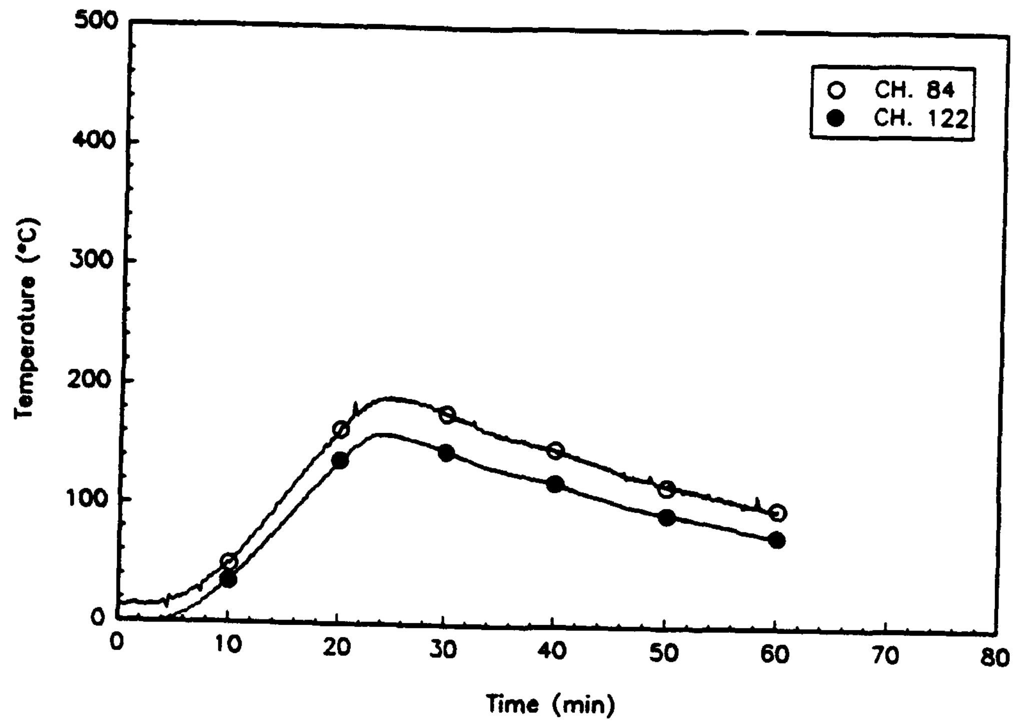

Fig. A158 – FR 81 bulkhead temperatures forward, INS_5A

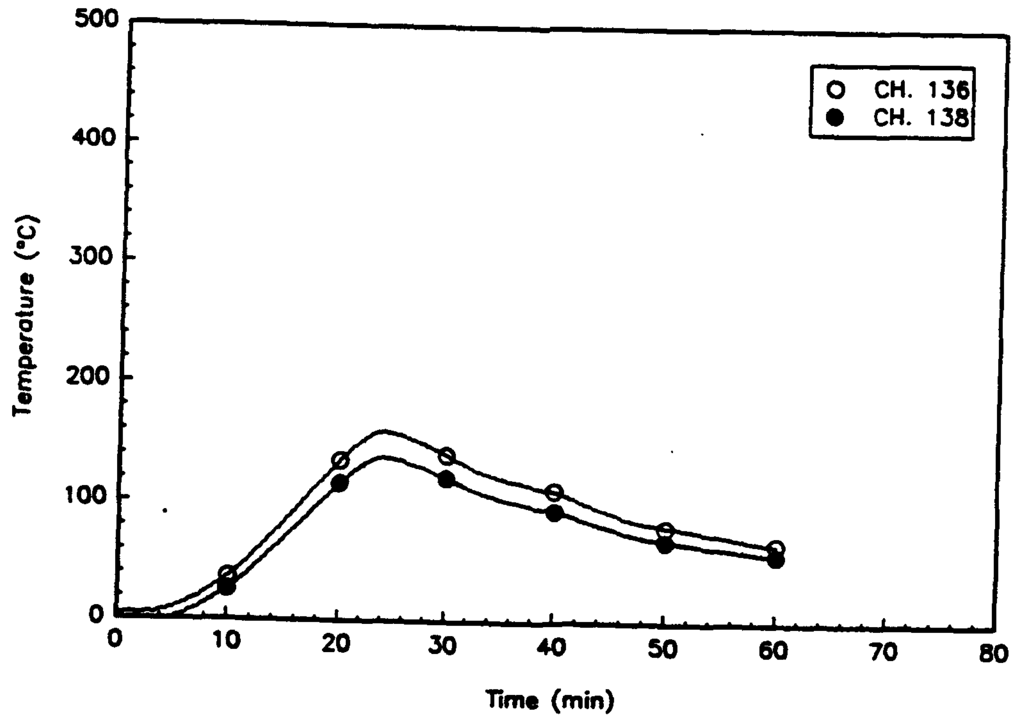

Fig. A159 – FR 88 bulkhead temperatures (RICER 2 side), INS_5A

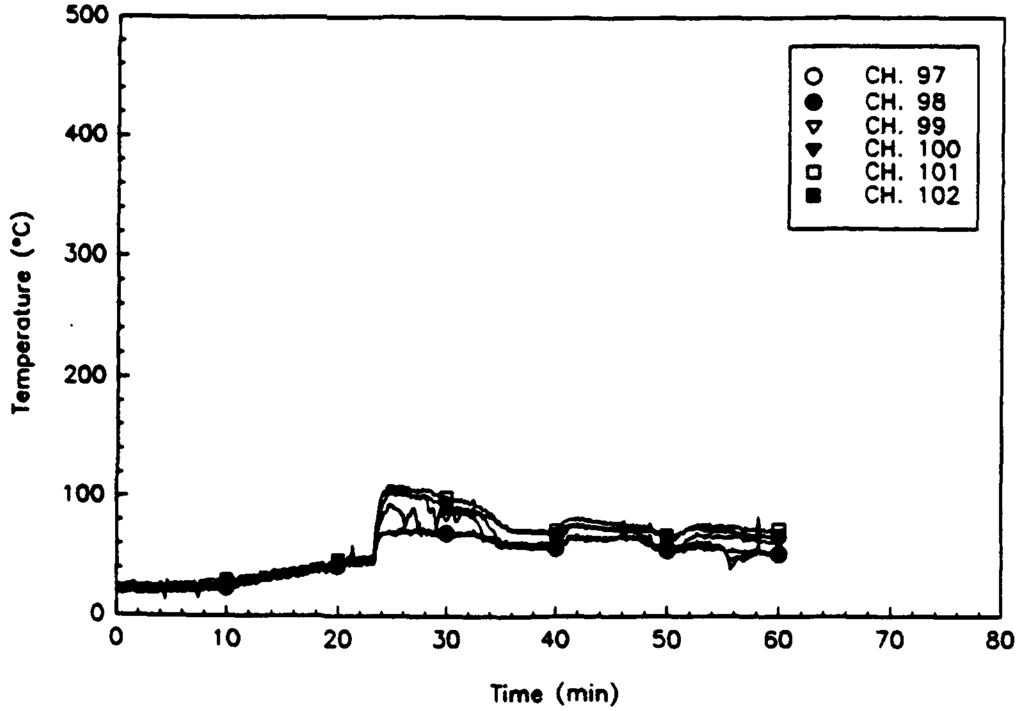

Fig. A160 – CIC air temperature aft, INS_5A

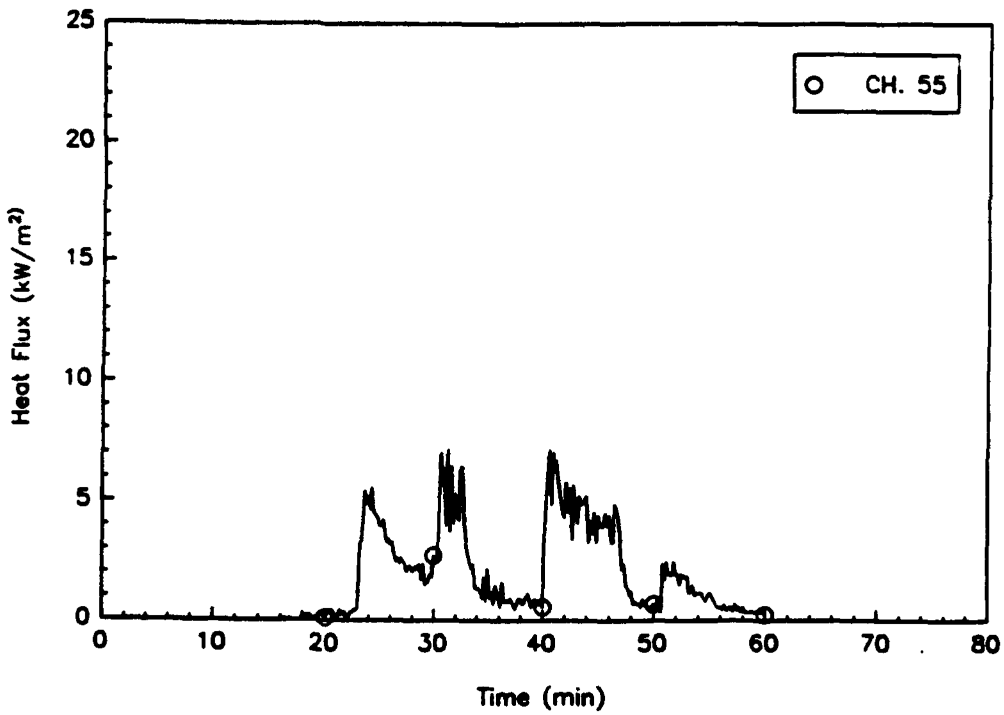

Fig. A161 – Total heat flux at CIC overhead, INS_5A

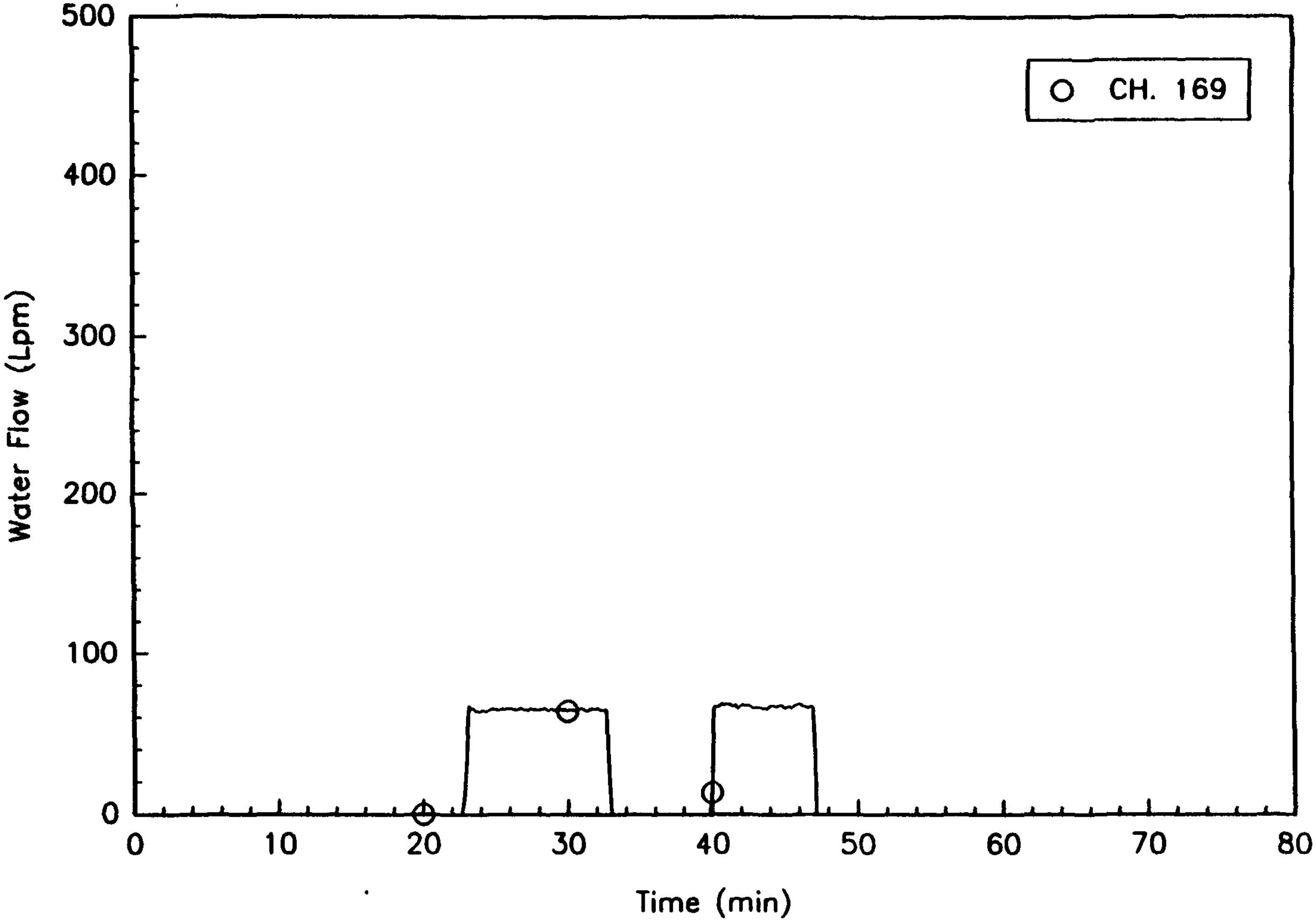

Fig A162 — Water flow from cooling handline, INS_5A

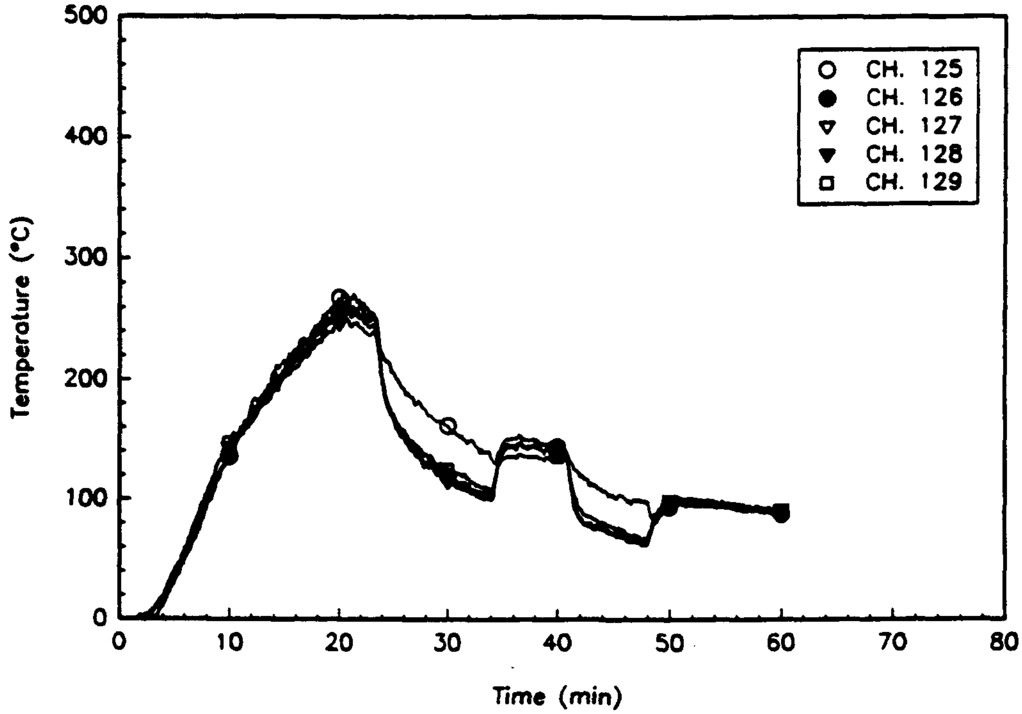

Fig. A163 – RICER 2 air temperatures forward, INS_6

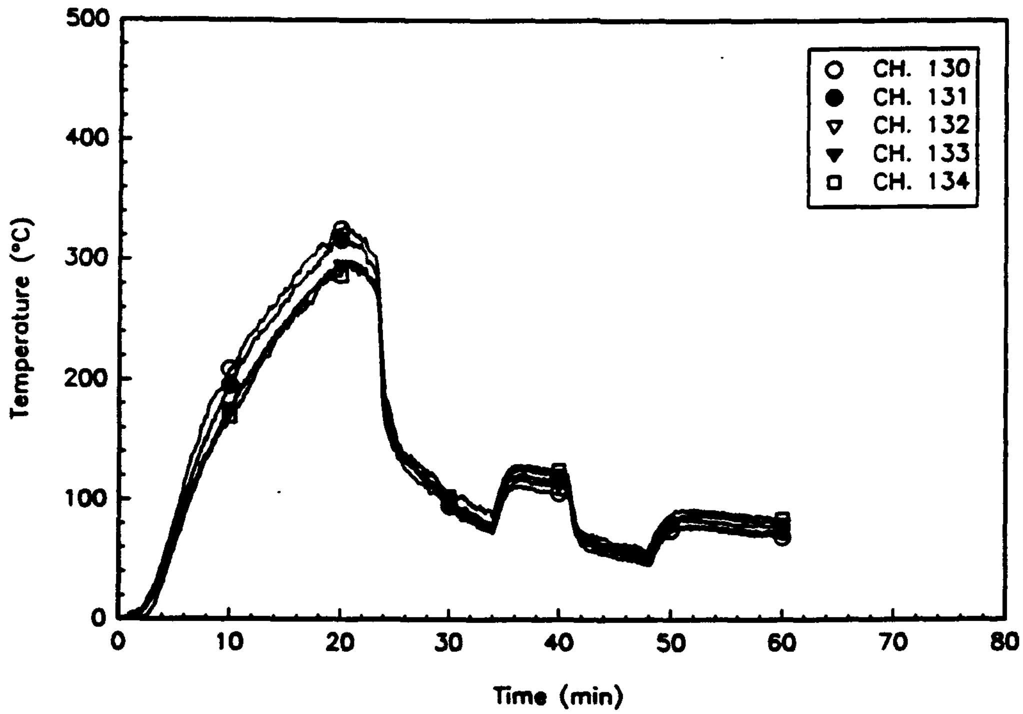

Fig. A164 – RICER 2 air temperatures aft, INS_6

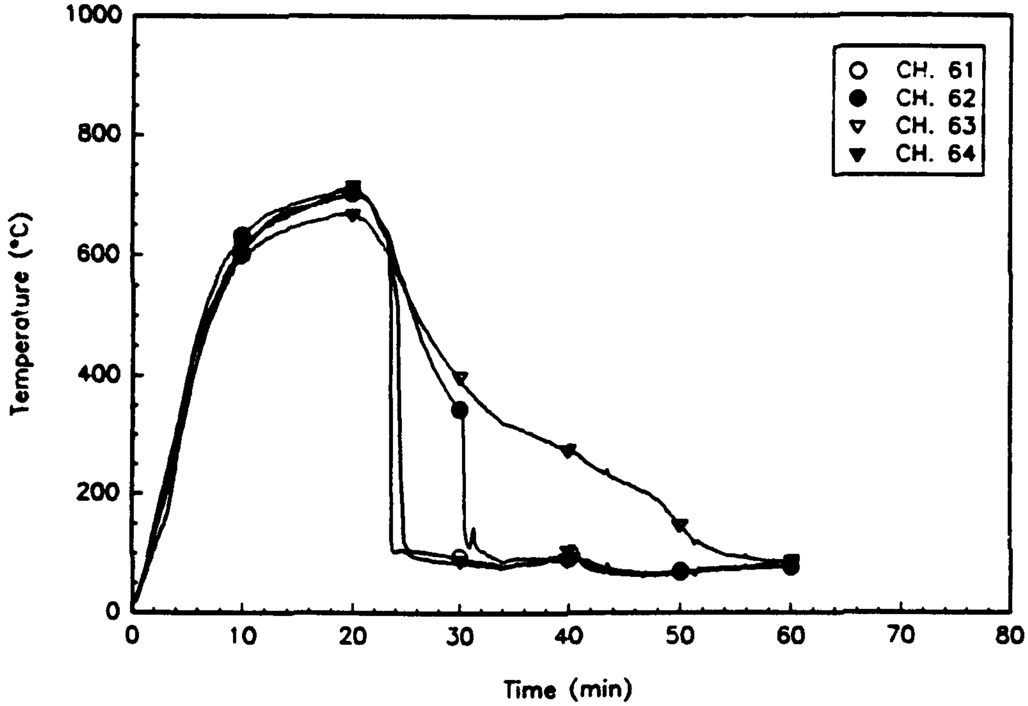

Fig. A165 – RICER 2 deck temperatures aft, INS_6

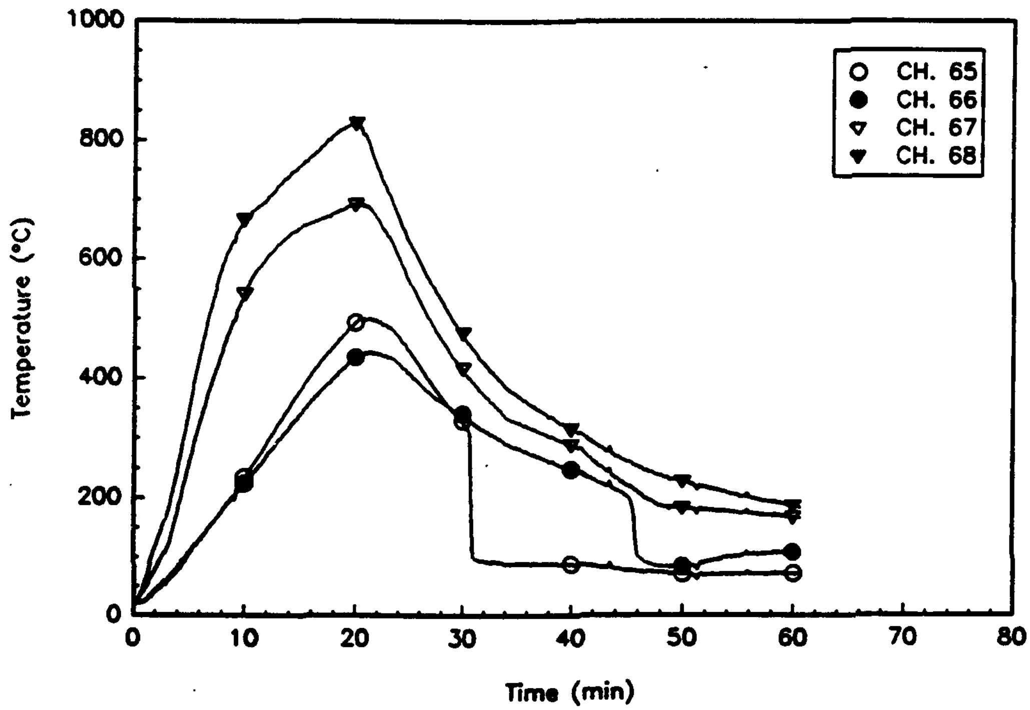

Fig. A166 – RICER 2 deck temperatures forward, INS_6

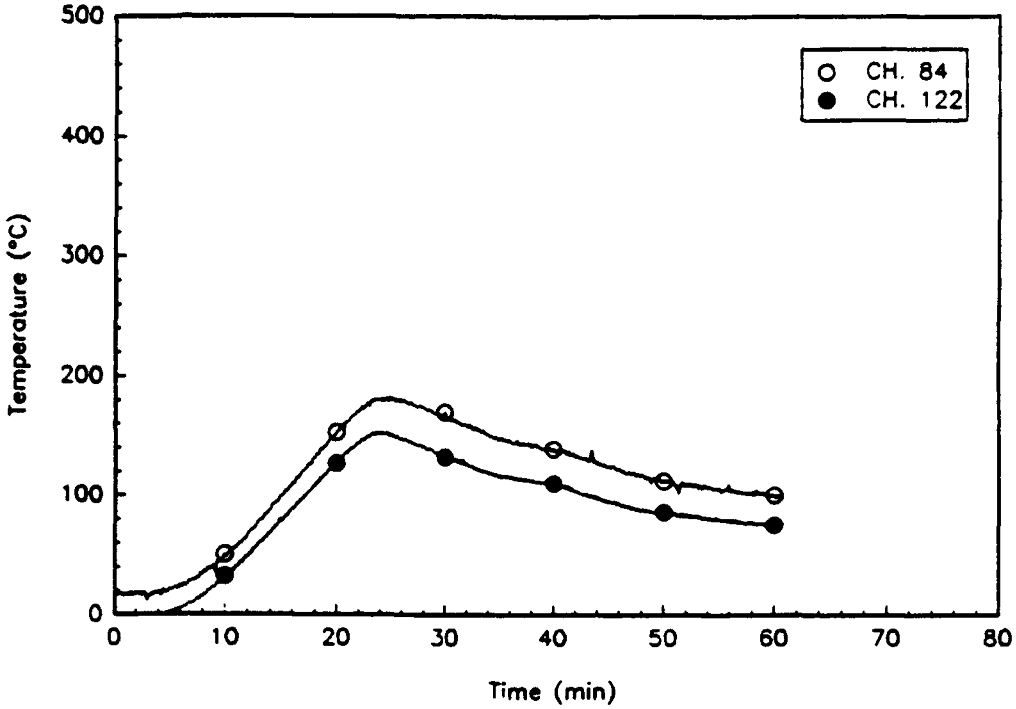

Fig. A167 — FR 81 bulkhead temperatures forward, INS_6

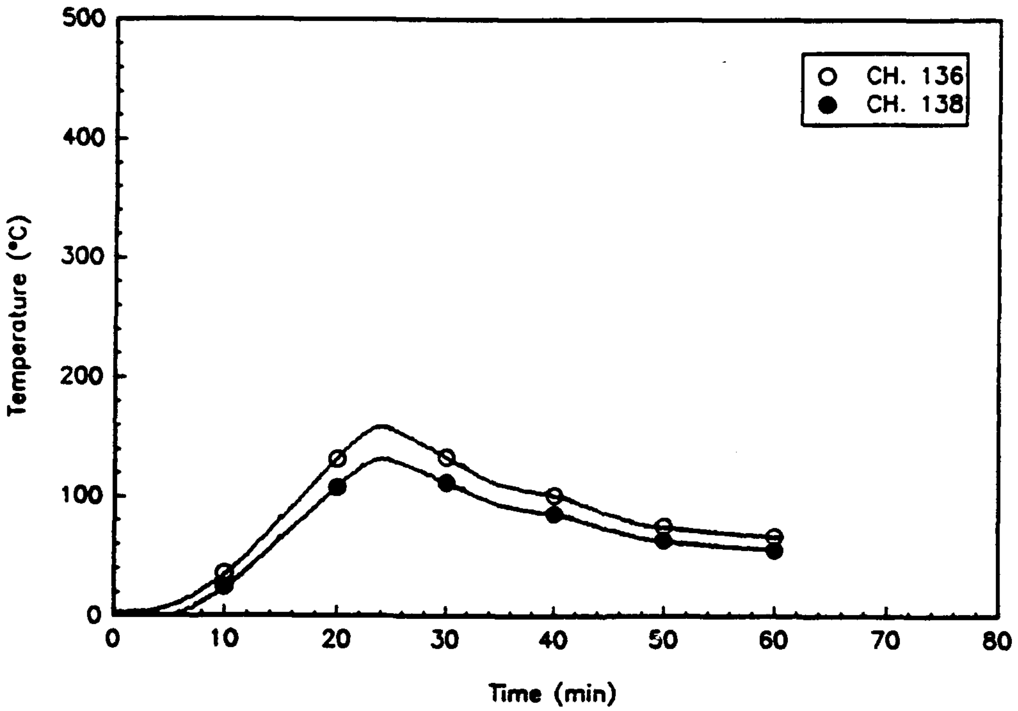

Fig. A168 — FR 88 bulkhead temperatures (RICER 2 side), INS_6

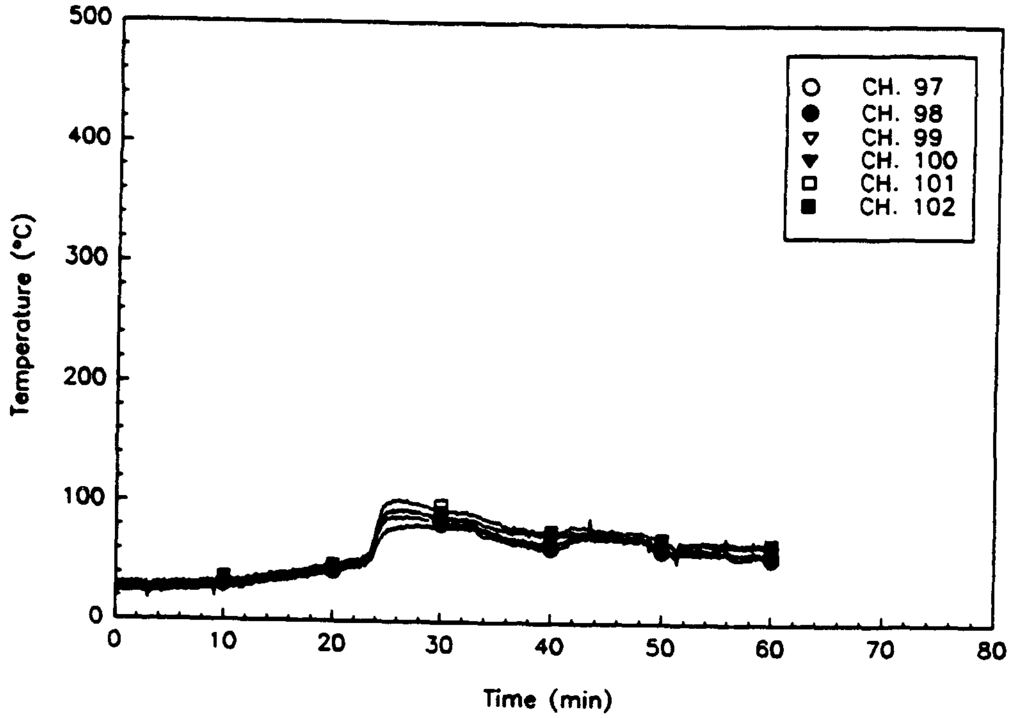

Fig. A169 – CIC air temperature aft, INS_6

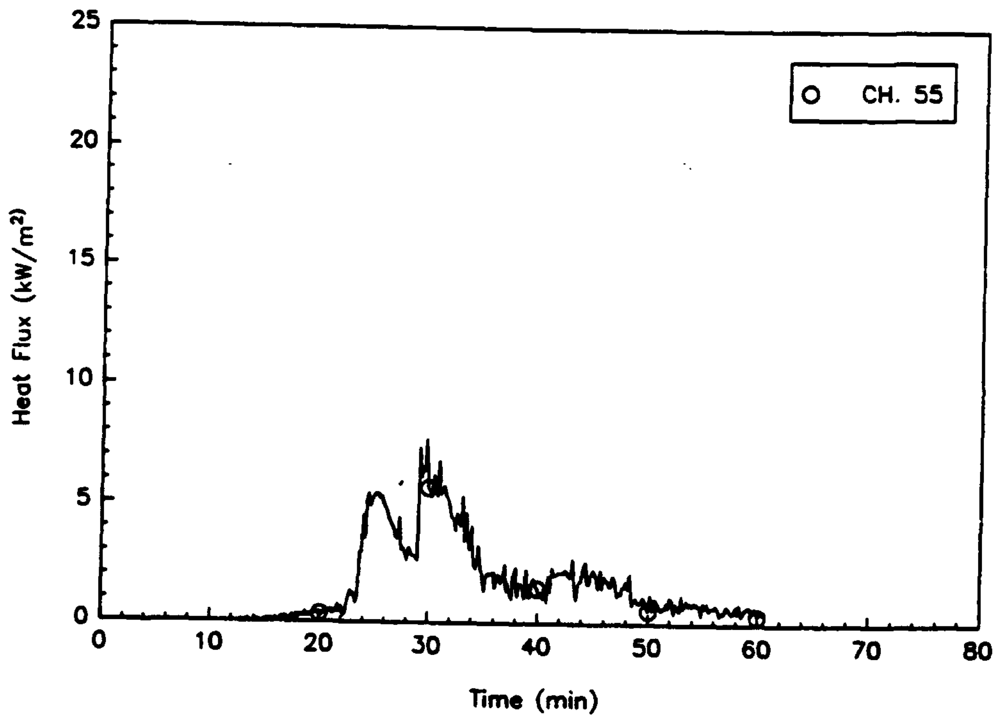

Fig. A170 – Total heat flux at CIC overhead, INS_6

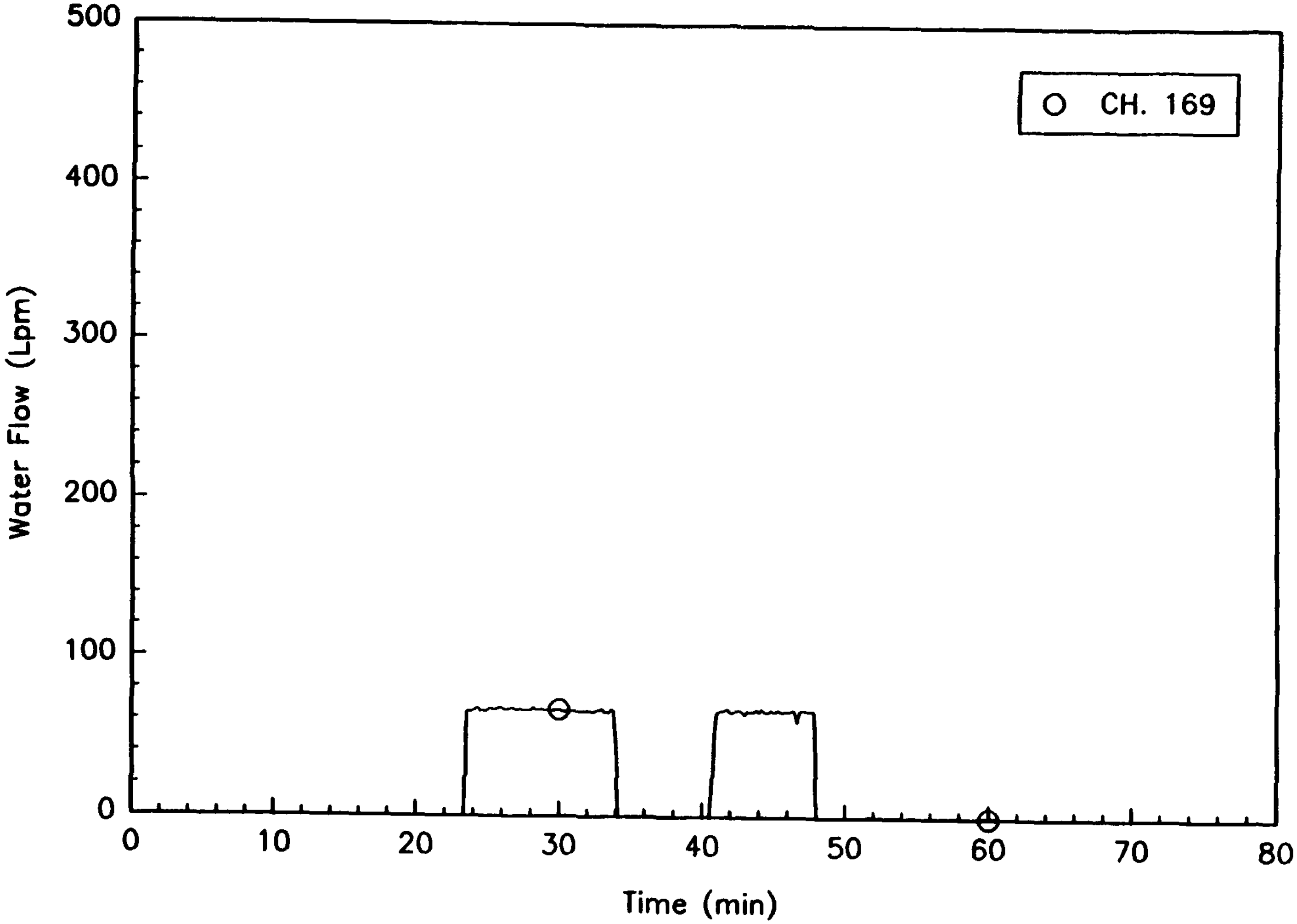

Fig. A171 — Water flow from cooling handline, INS_6

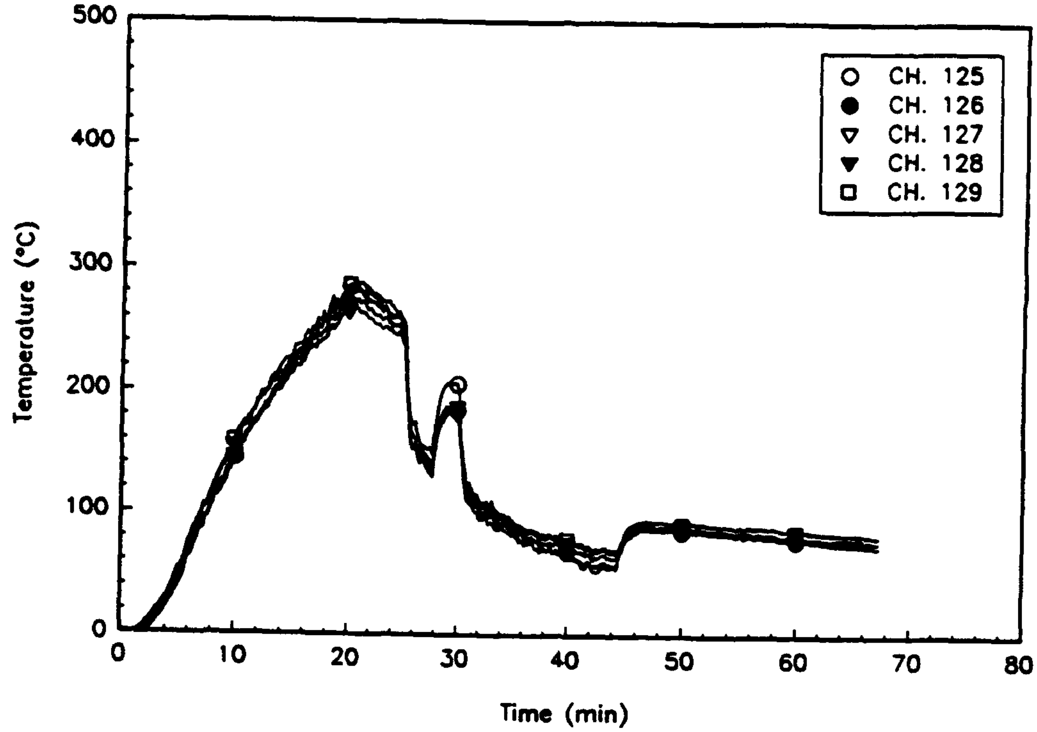

Fig. A172 – RICER 2 air temperatures forward, INS_7

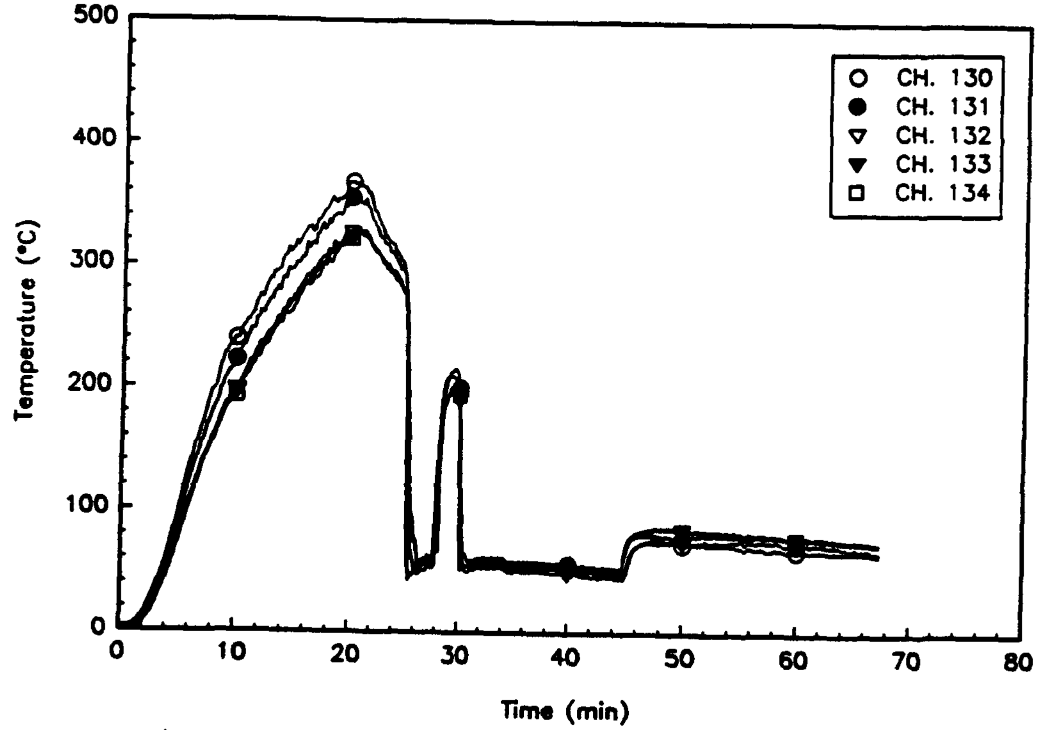

Fig. A173 – RICER 2 air temperature aft, INS_7

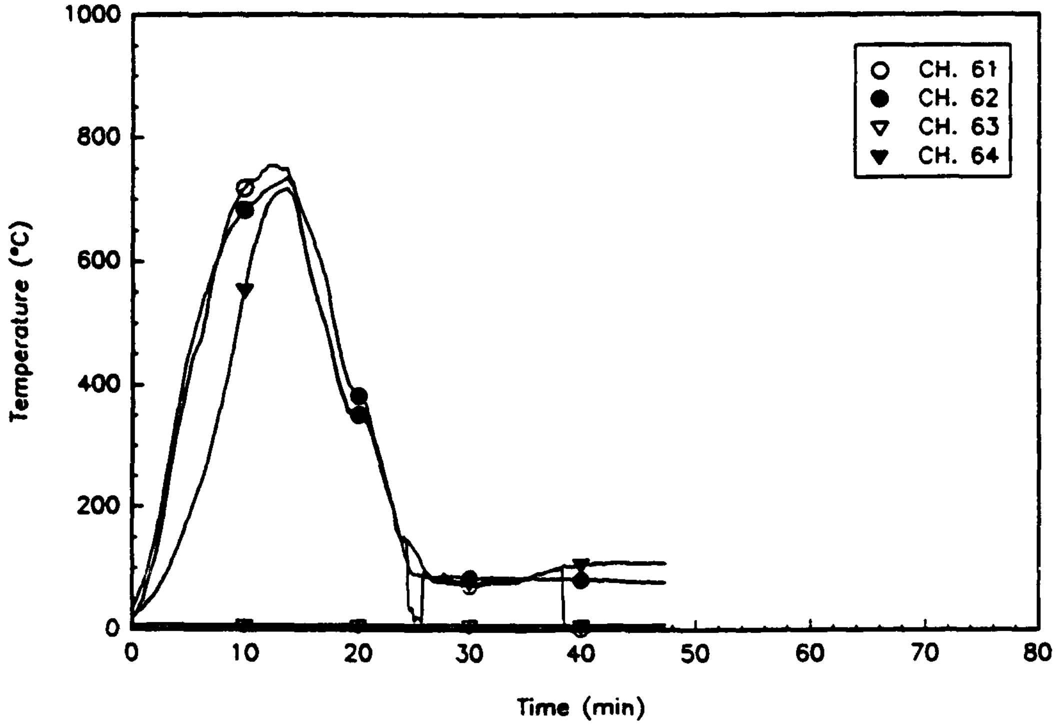

Fig. A174 – RICER 2 deck temperatures aft, INS_7

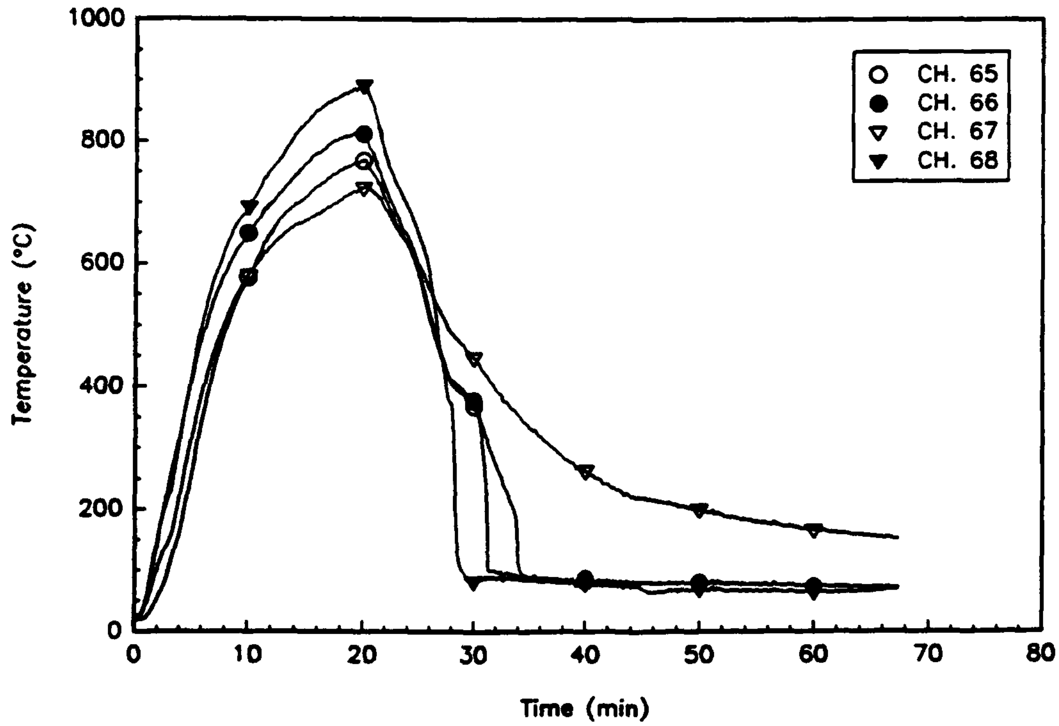

Fig. A175 – RICER 2 deck temperatures forward, INS_7

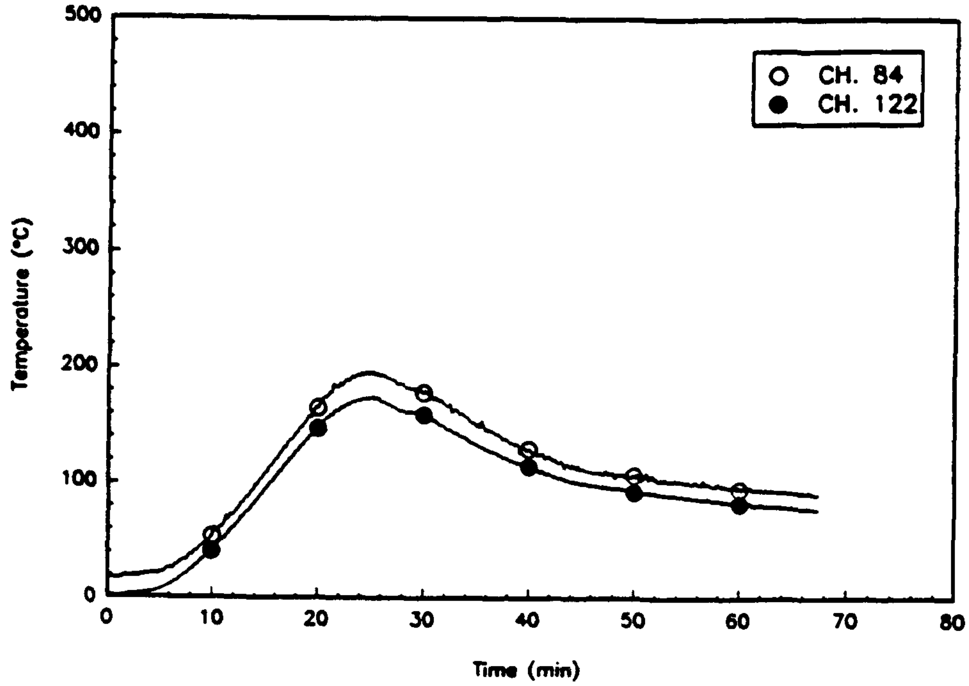

Fig. A176 – FR81 bulkhead temperatures forward, INS_7

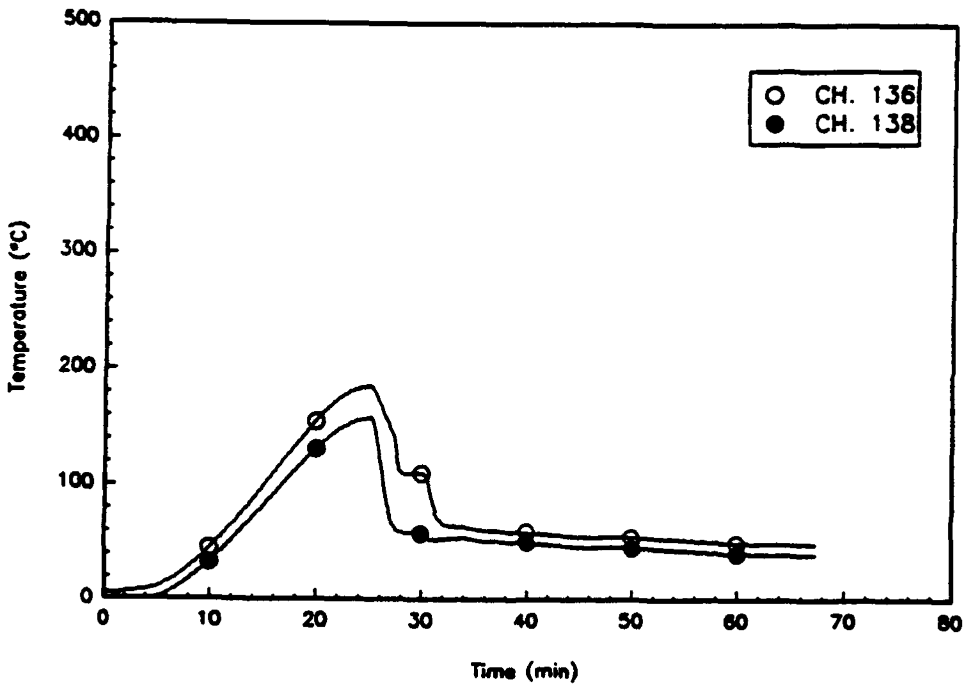

Fig. A177 – FR88 bulkhead temperatures (RICER 2 side), INS_7

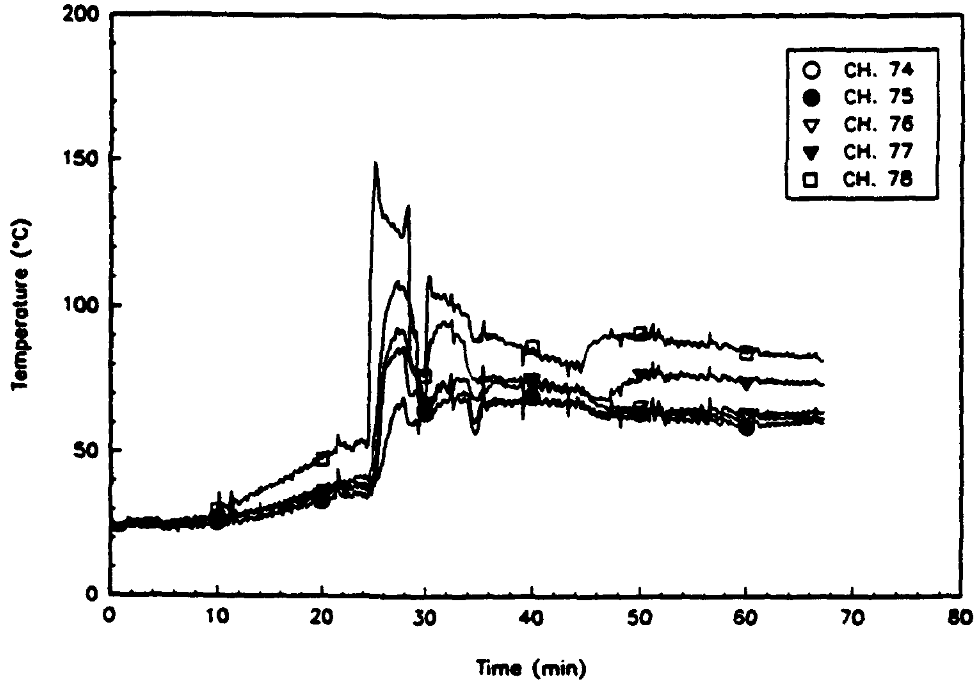

Fig. A178 – RICER 1 air temperatures, INS_7

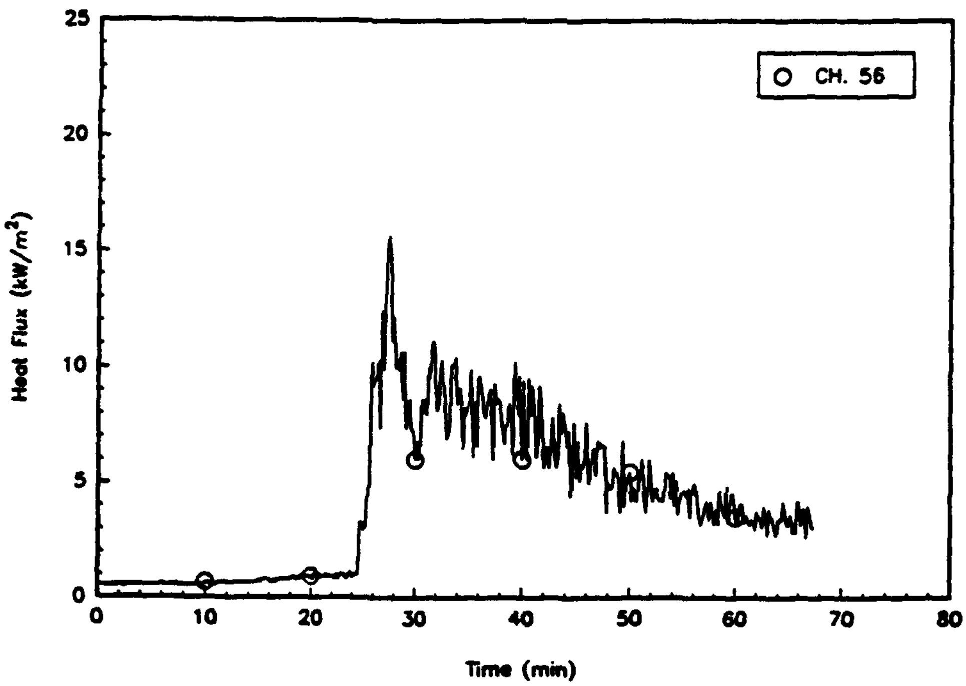

Fig. A179 – Total heat flux at RICER 1 overhead, INS_7

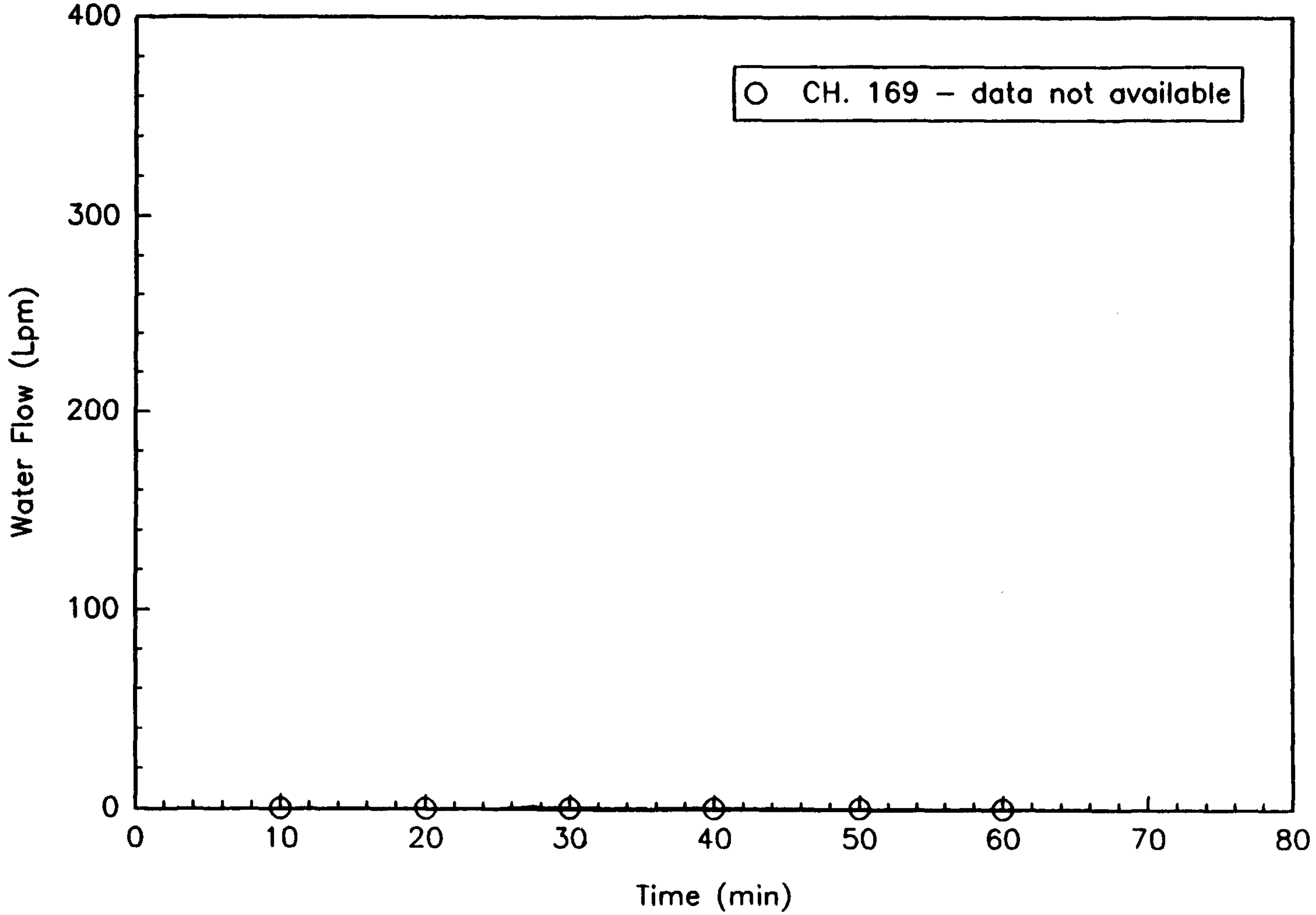

Fig. A180 – Water flow from cooling handline, COL_7

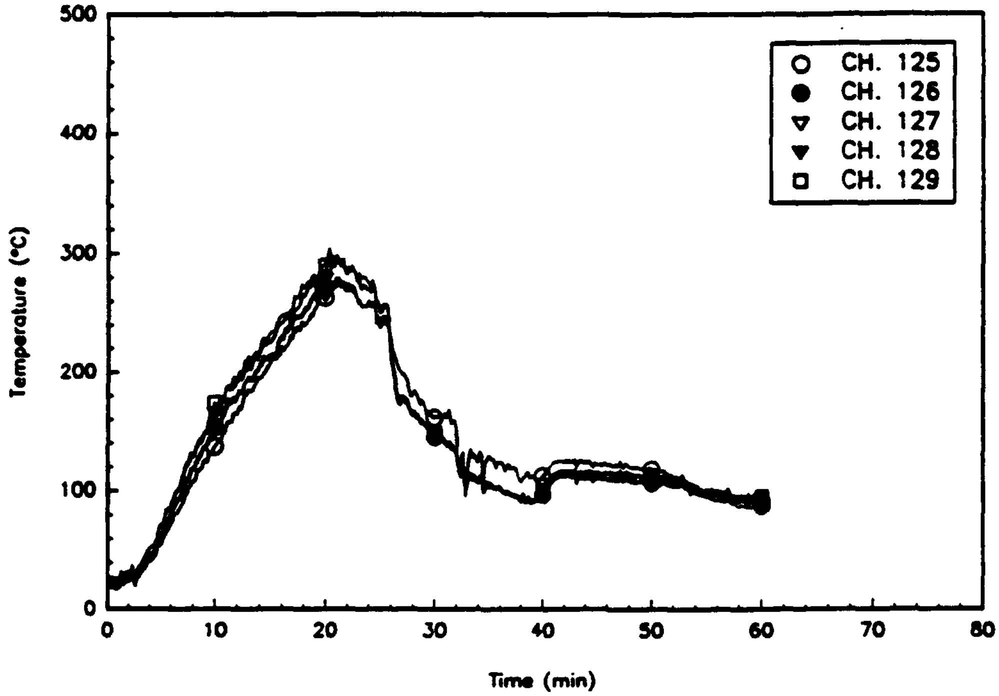

Fig. A181 — RICER 2 air temperatures forward, INS_8

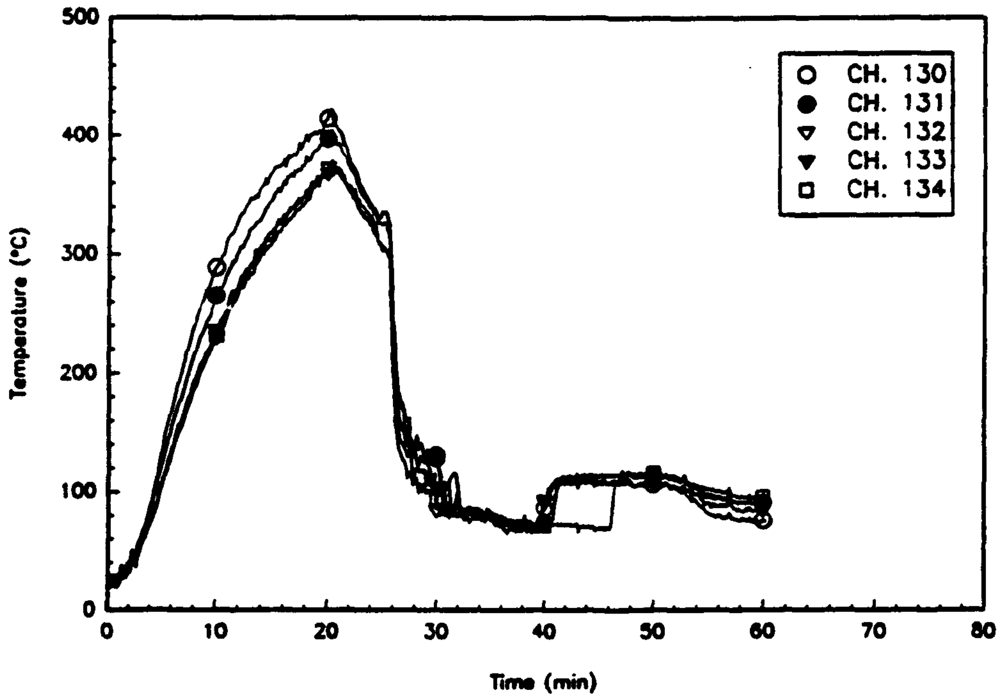

Fig. A182 — RICER 2 air temperatures aft, INS_8

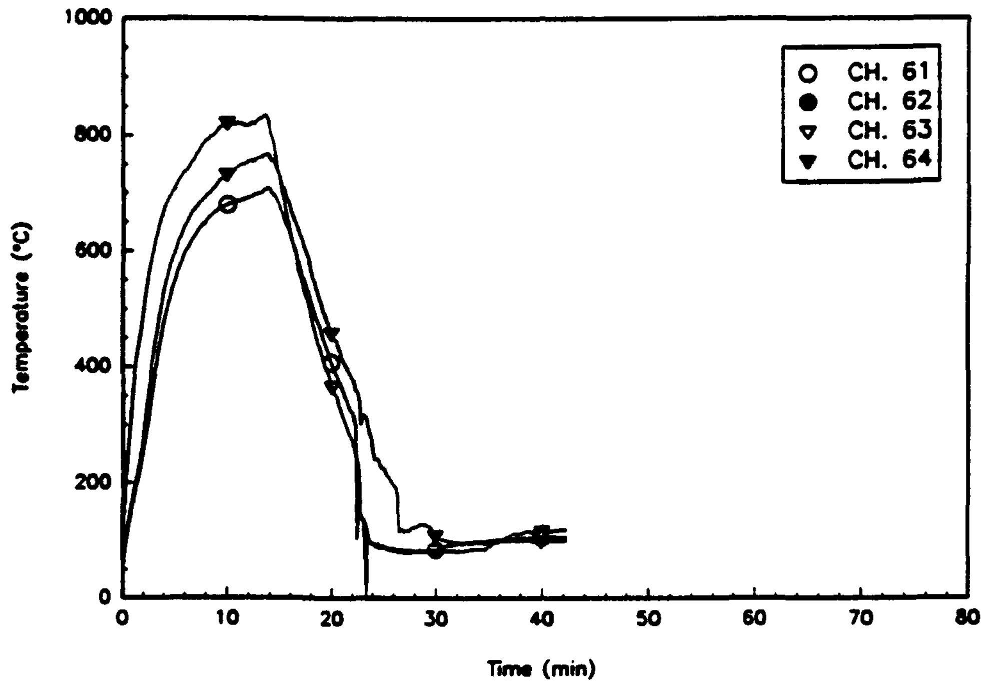

Fig. A183 – RICER 2 deck temperature aft, INS_8

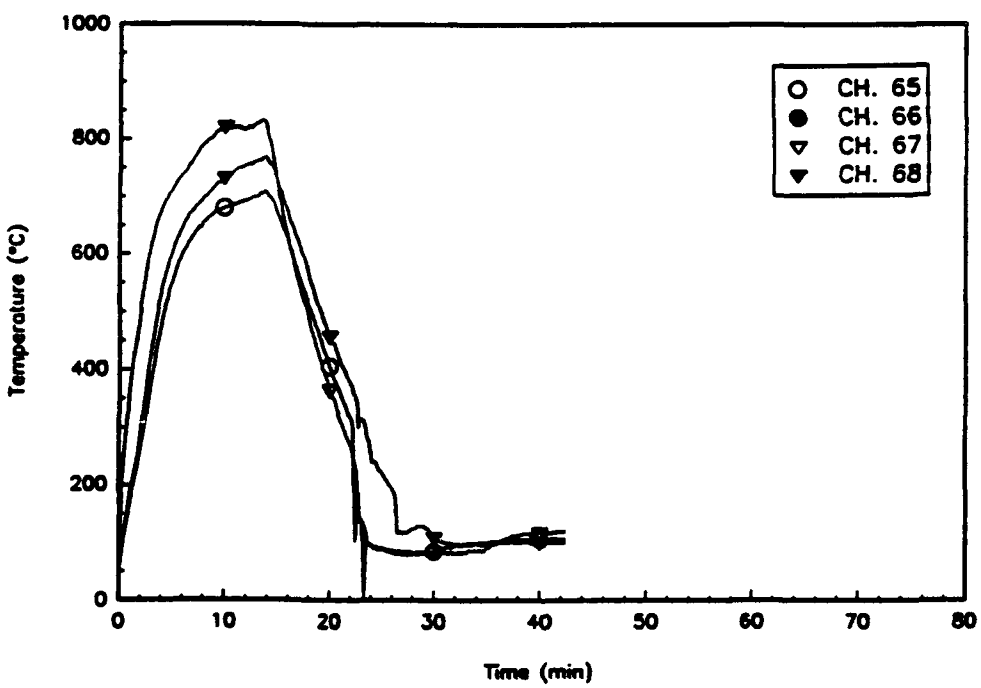

Fig. A184 – RICER 2 deck temperatures forward, INS_8

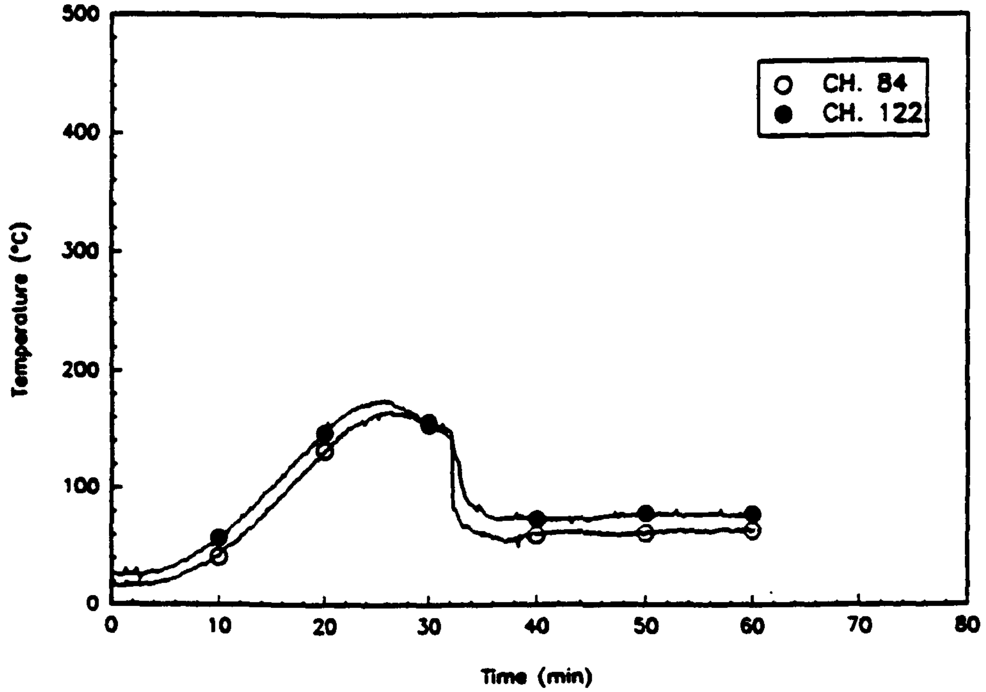

Fig. A185 – FR81 bulkhead temperatures forward, INS_8

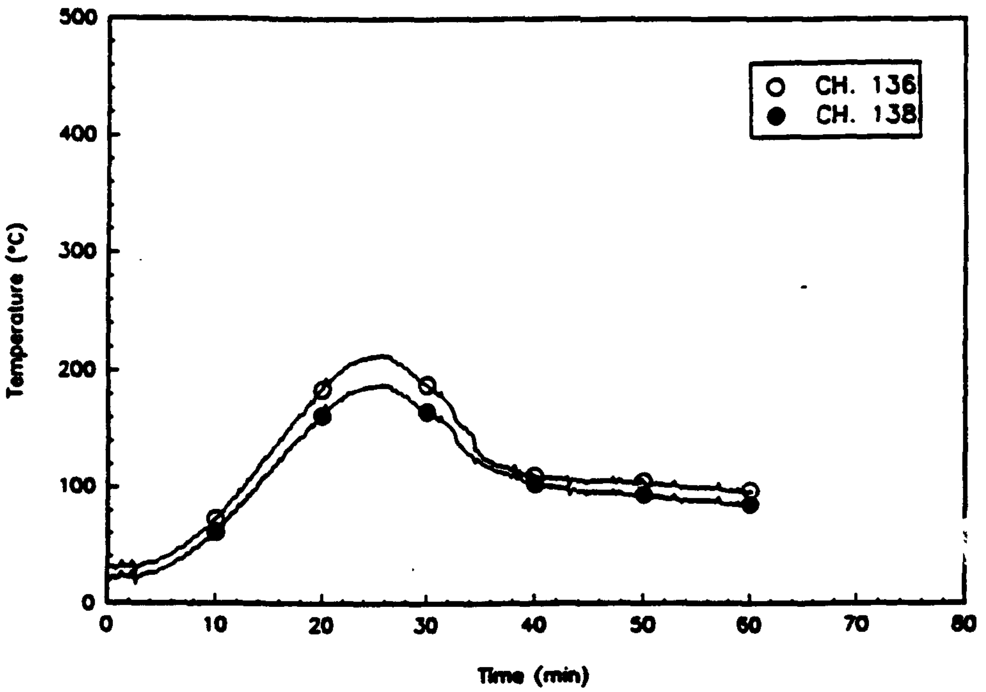

Fig. A186 – FR88 bulkhead temperatures
(RICER 2 side), INS_8

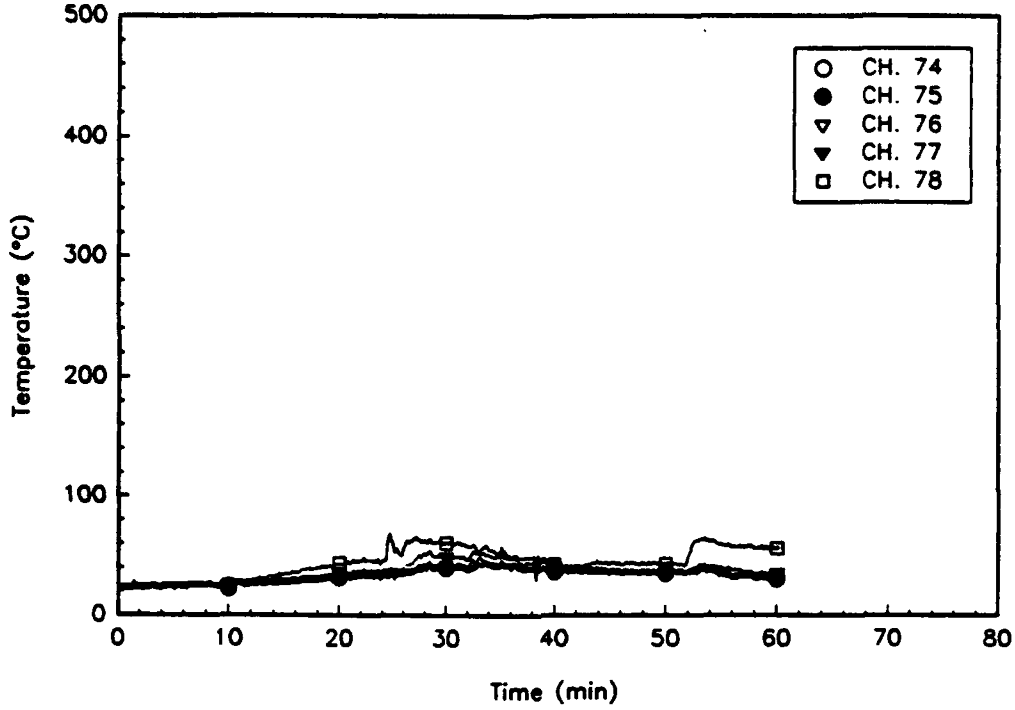

Fig. A187 — RICER 1 air temperatures, INS_8

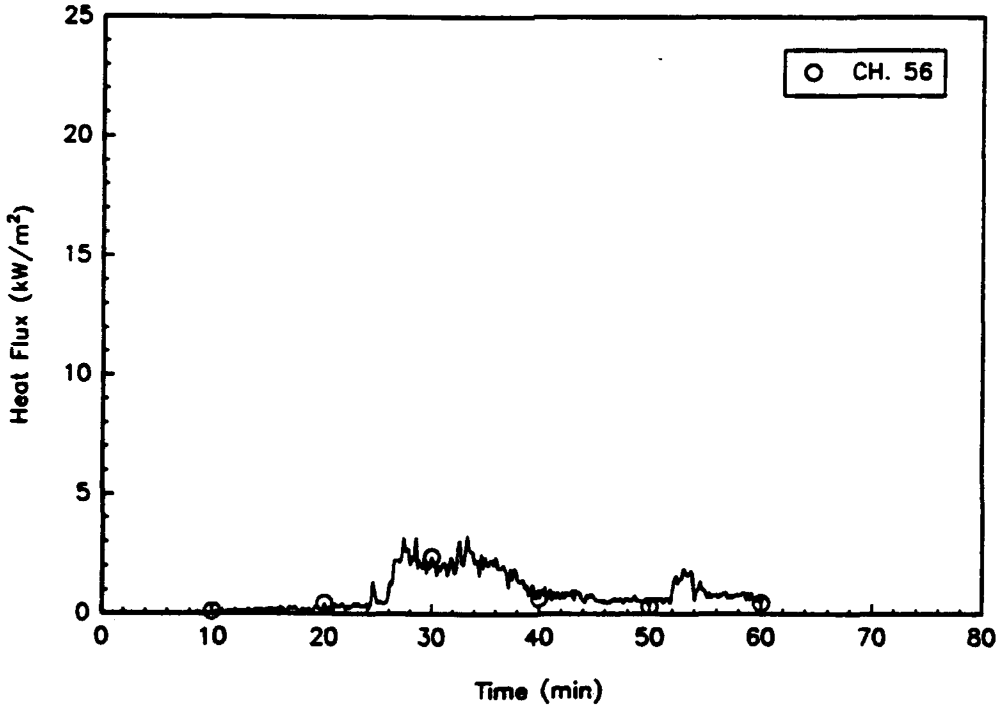

Fig. A188 — Total heat flux at RICER 1 overhead, INS_8

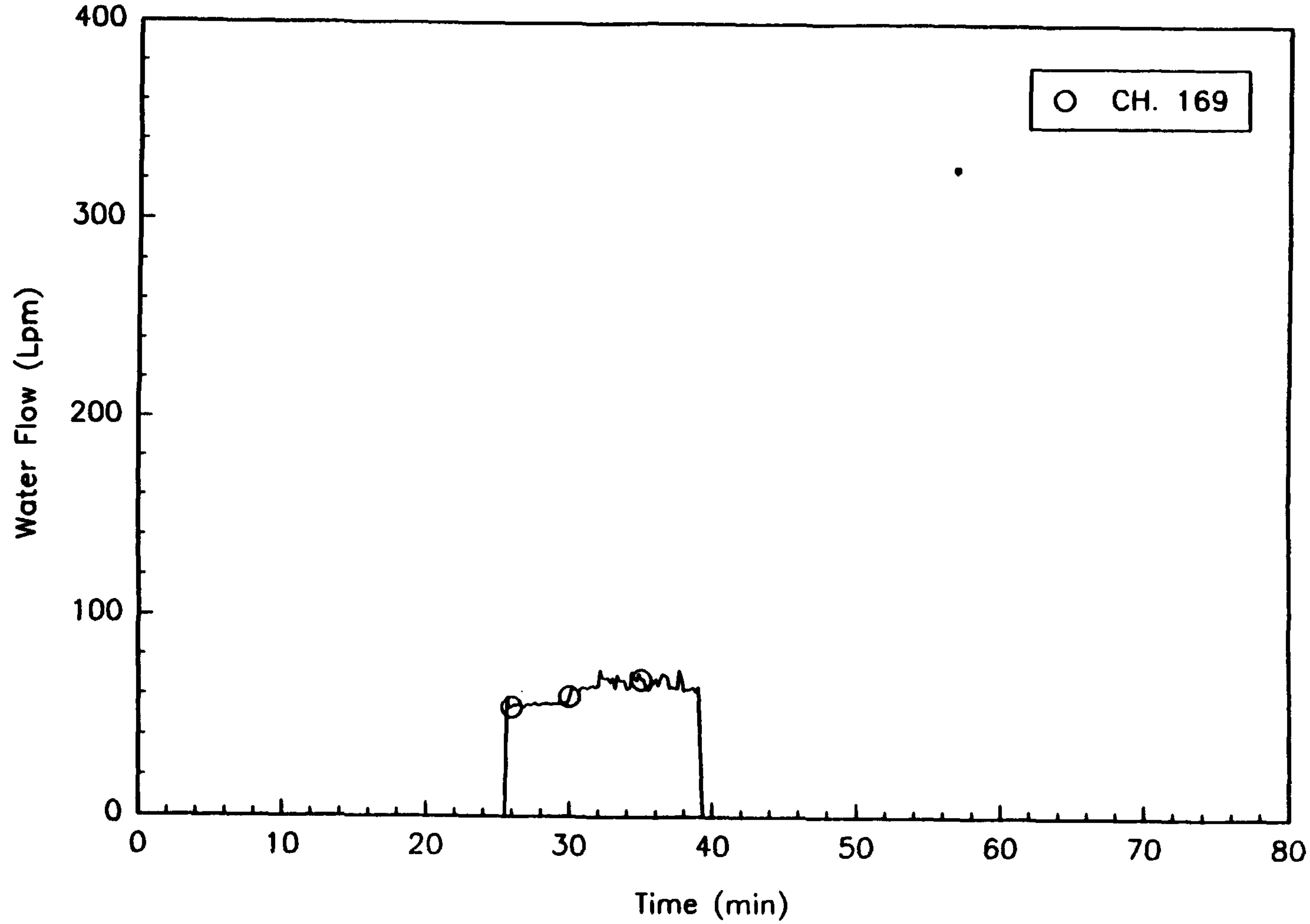

Fig. A189 — Water flow from cooling handline, INS_8

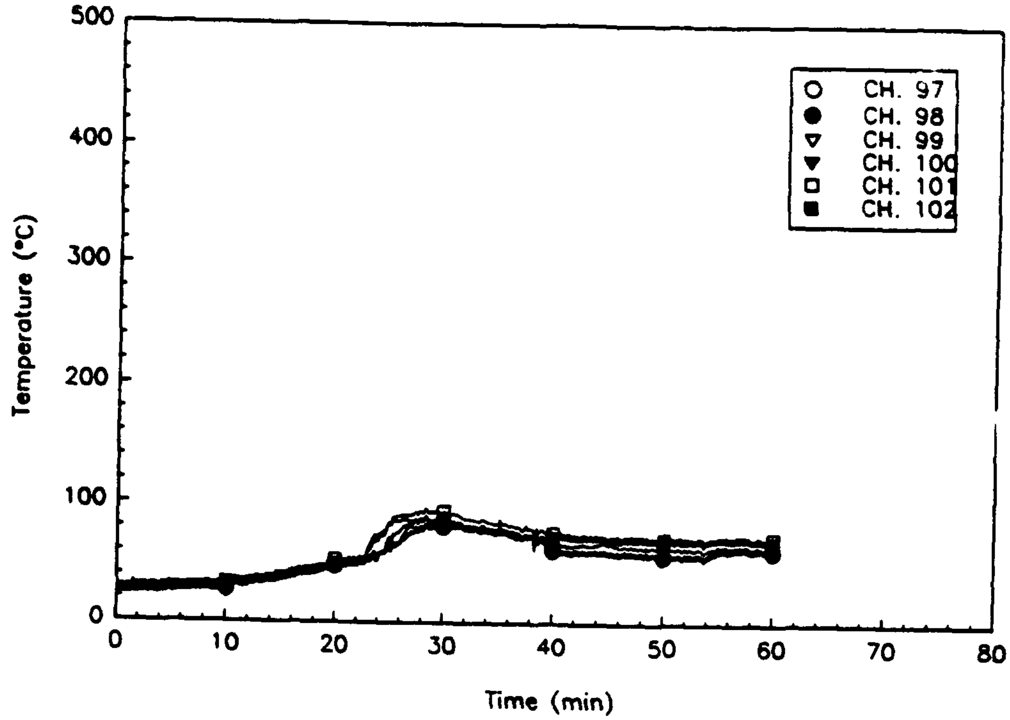

Fig. A190 – CIC air temperature aft, INS_8

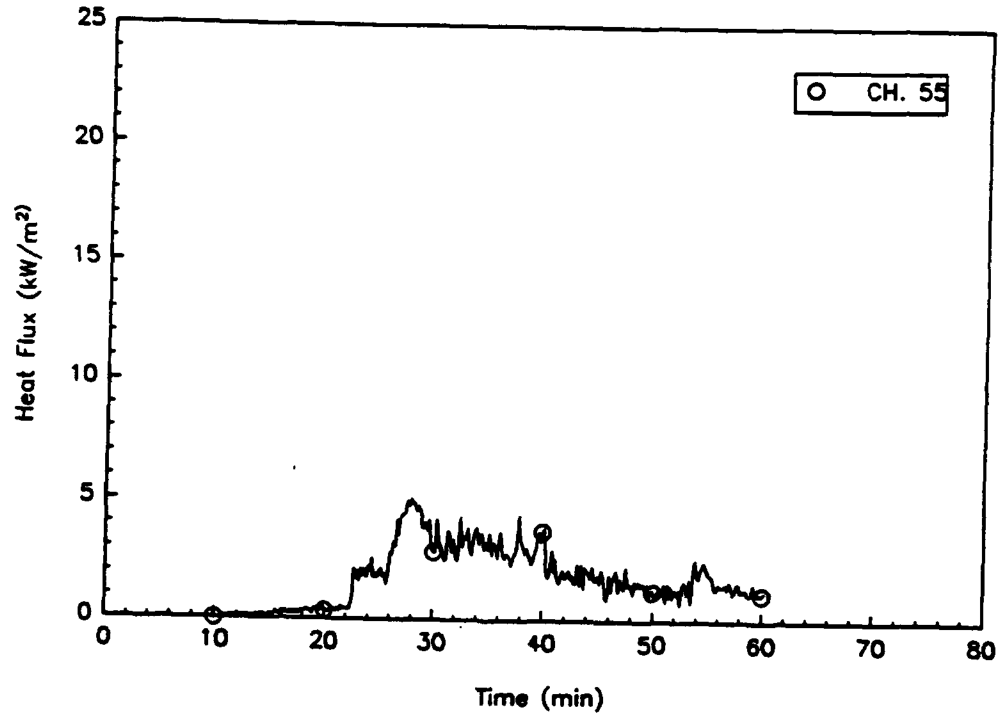

Fig. A191 – Total heat flux at CIC overhead, INS_8

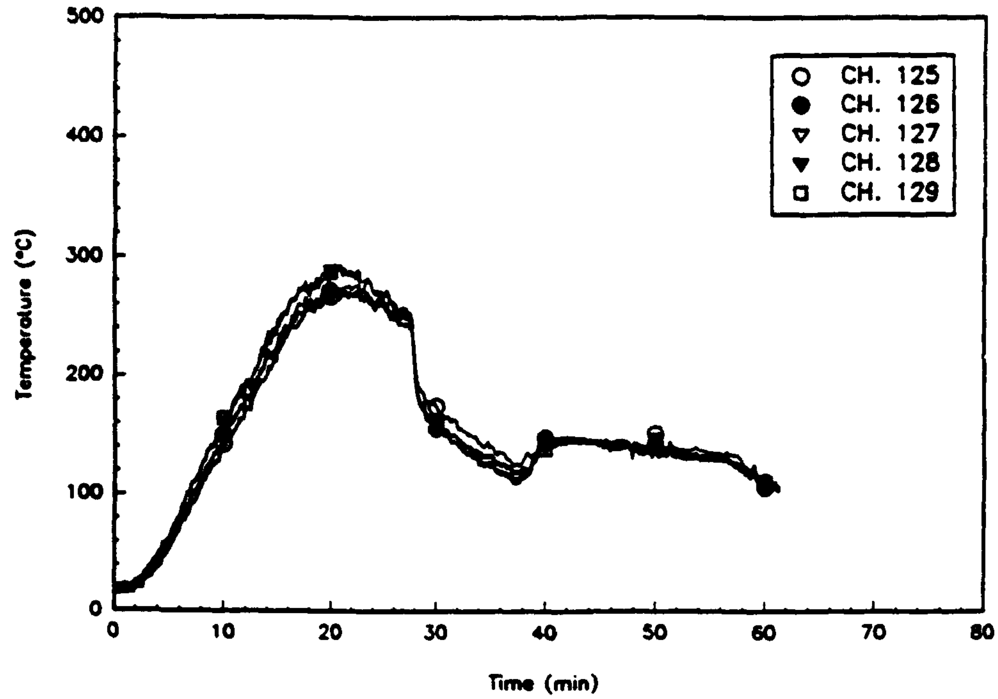

Fig. A192 – RICER 2 air temperature forward, INS_9

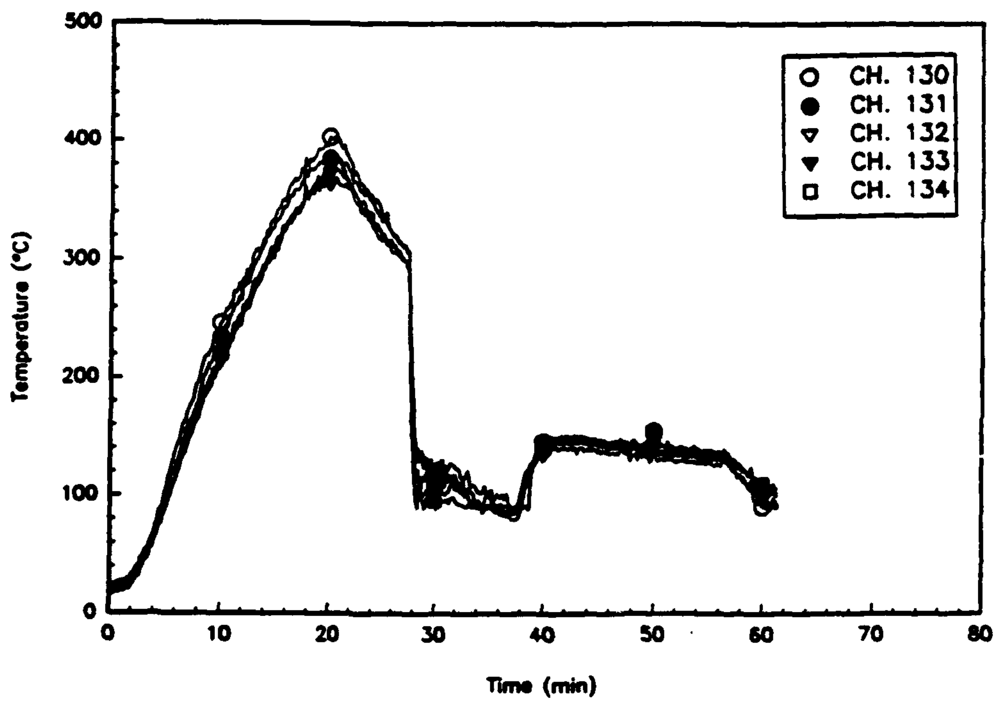

Fig. A193 – RICER 2 air temperature aft, INS_9

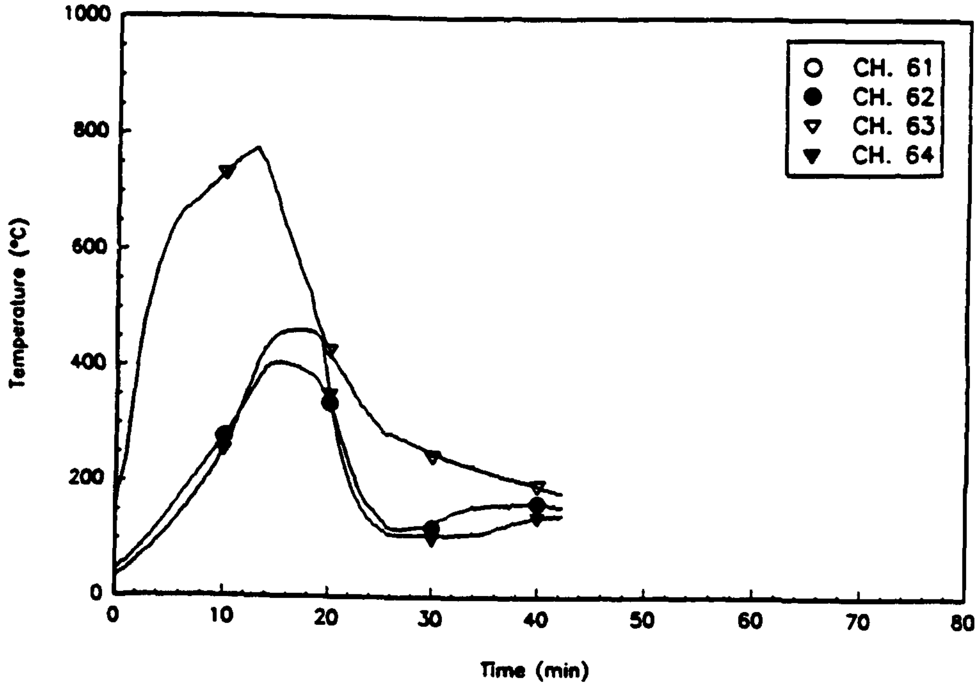

Fig. A194 – RICER 2 deck temperatures aft, INS_9

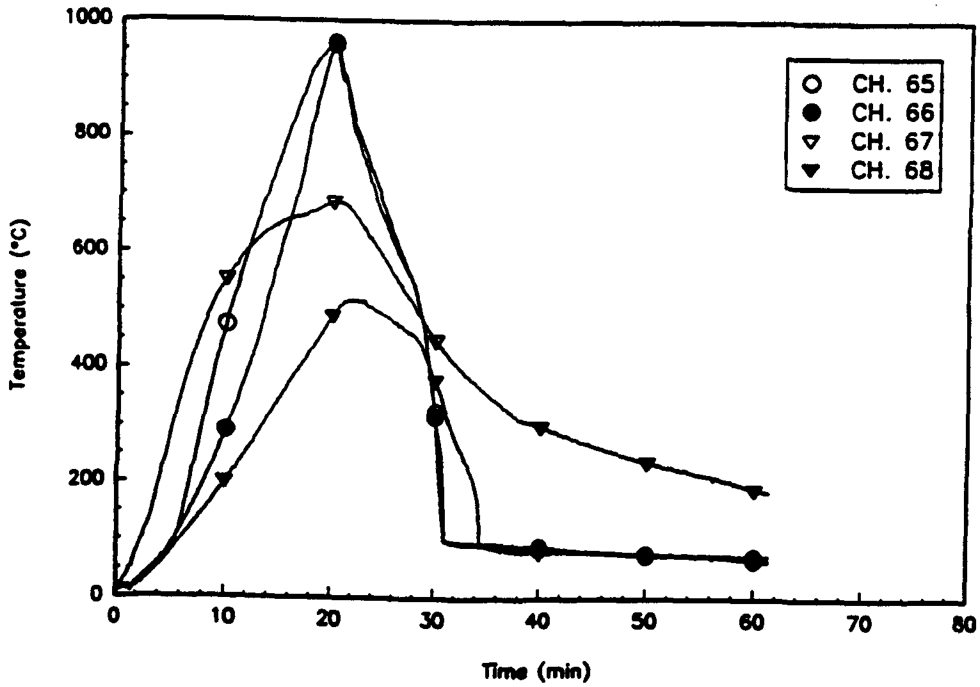

Fig. A195 – RICER 2 deck temperatures forward, INS_9

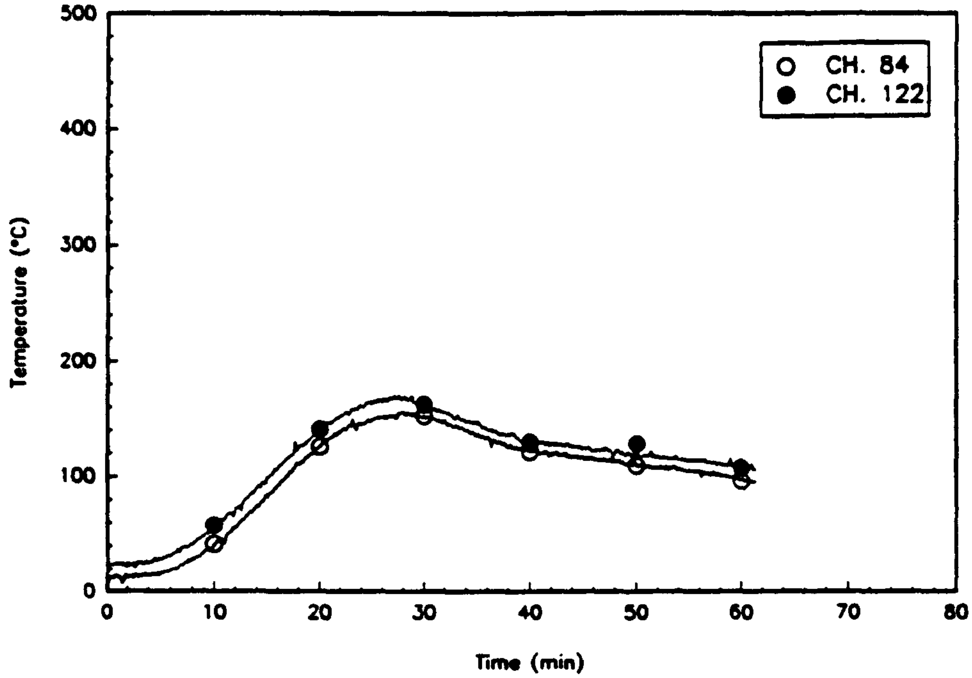

Fig. A196 – FR81 bulkhead temperatures forward, INS_9

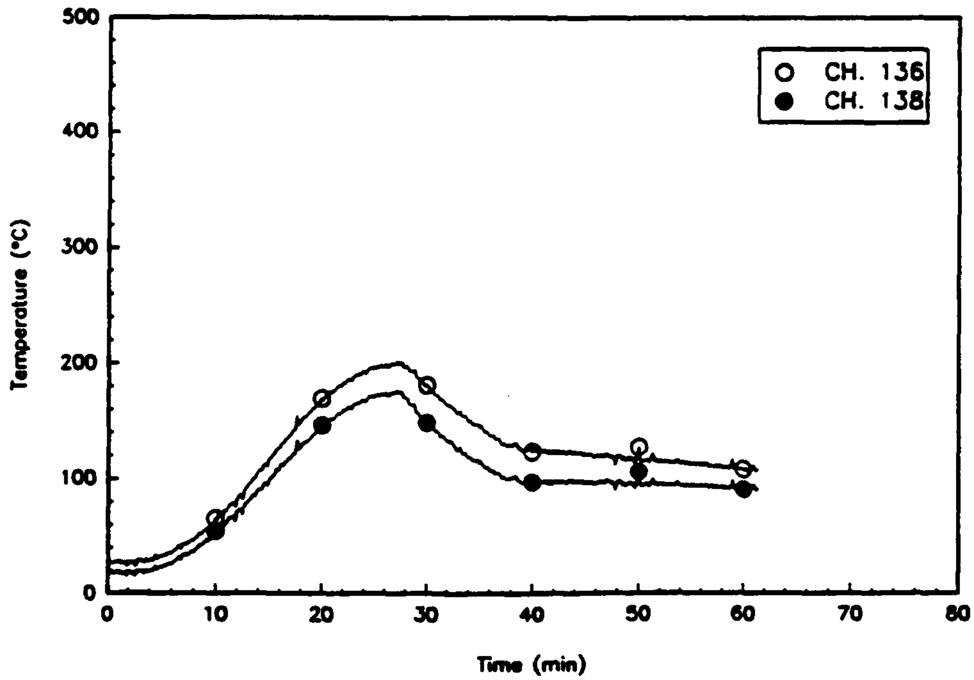

Fig. A197 – FR88 bulkhead temperatures (RICER 2 side), INS_9

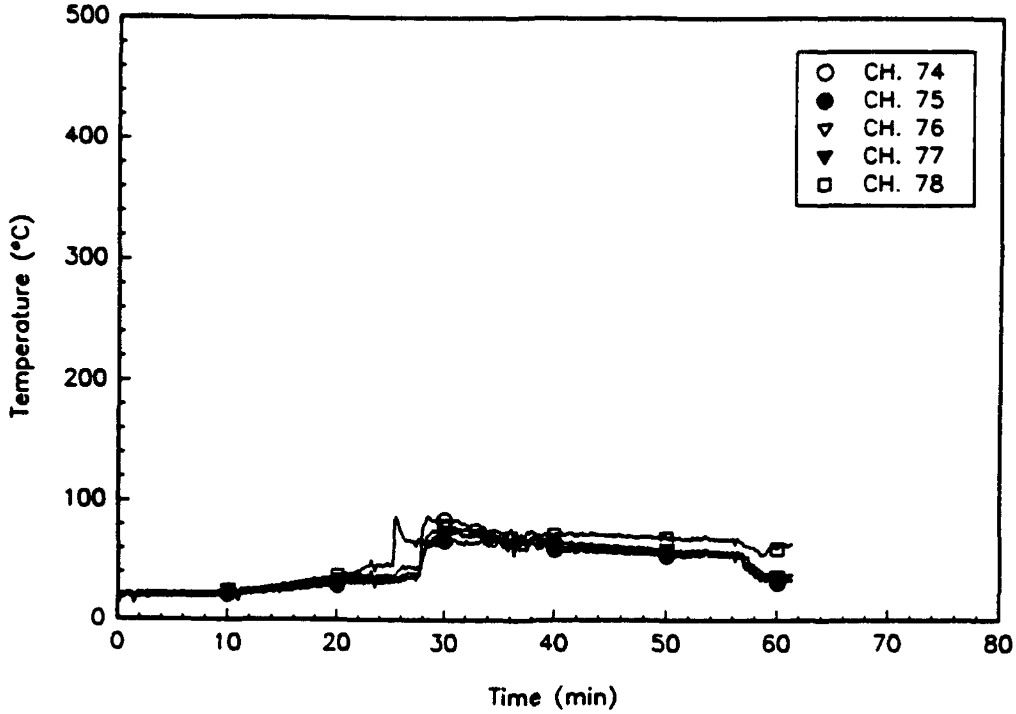

Fig. A198 – RICER 1 air temperatures, INS_9

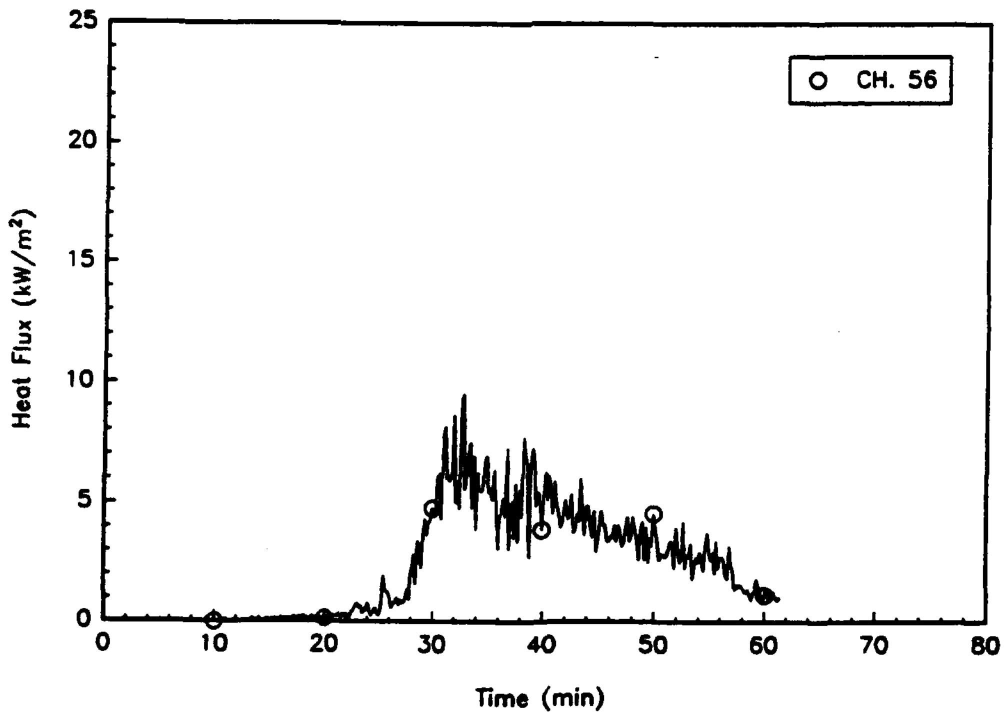

Fig. A199 – Total heat flux at RICER 1 overhead, INS_9

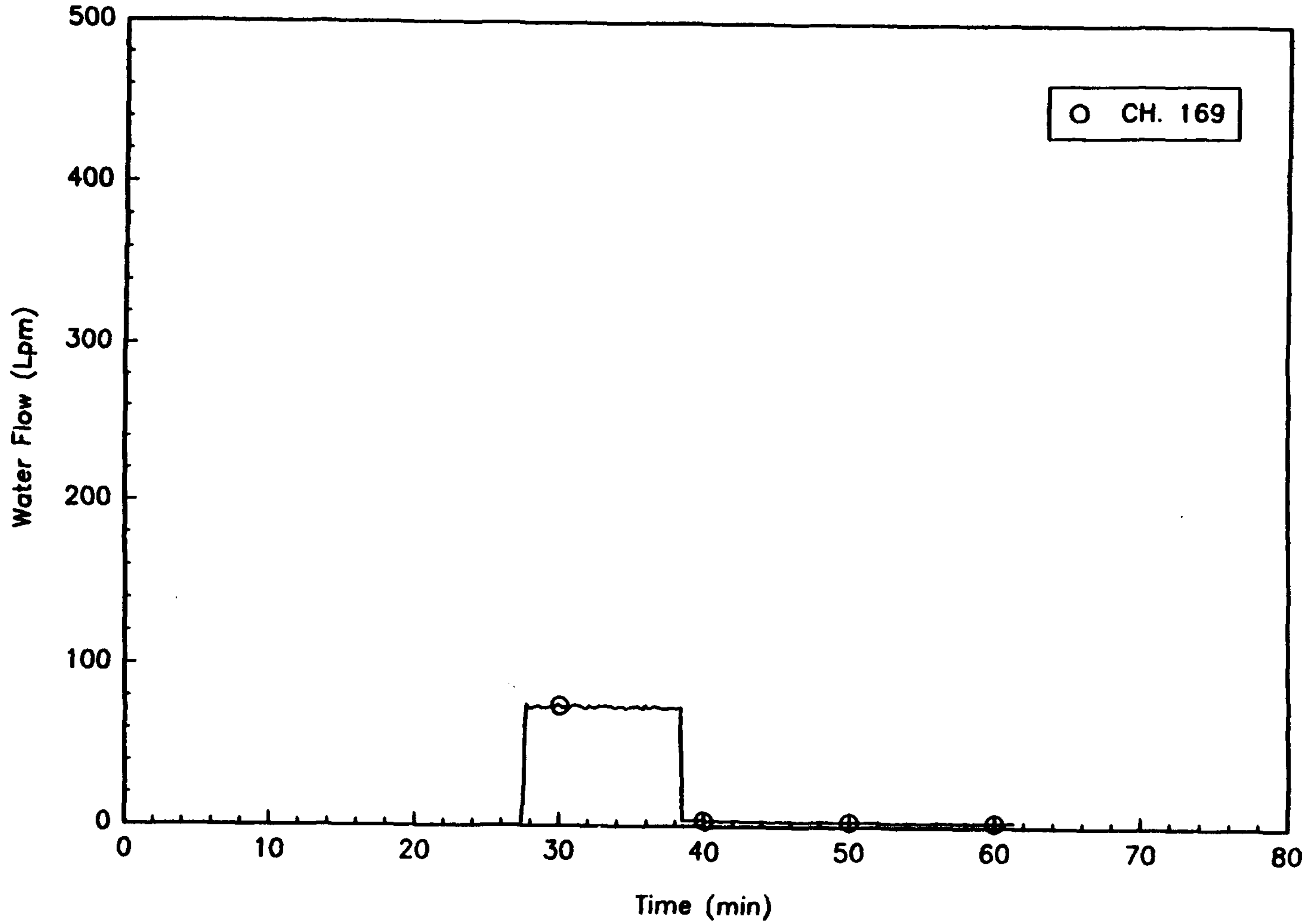

Fig A200 — Water flow from cooling handline, INS_9

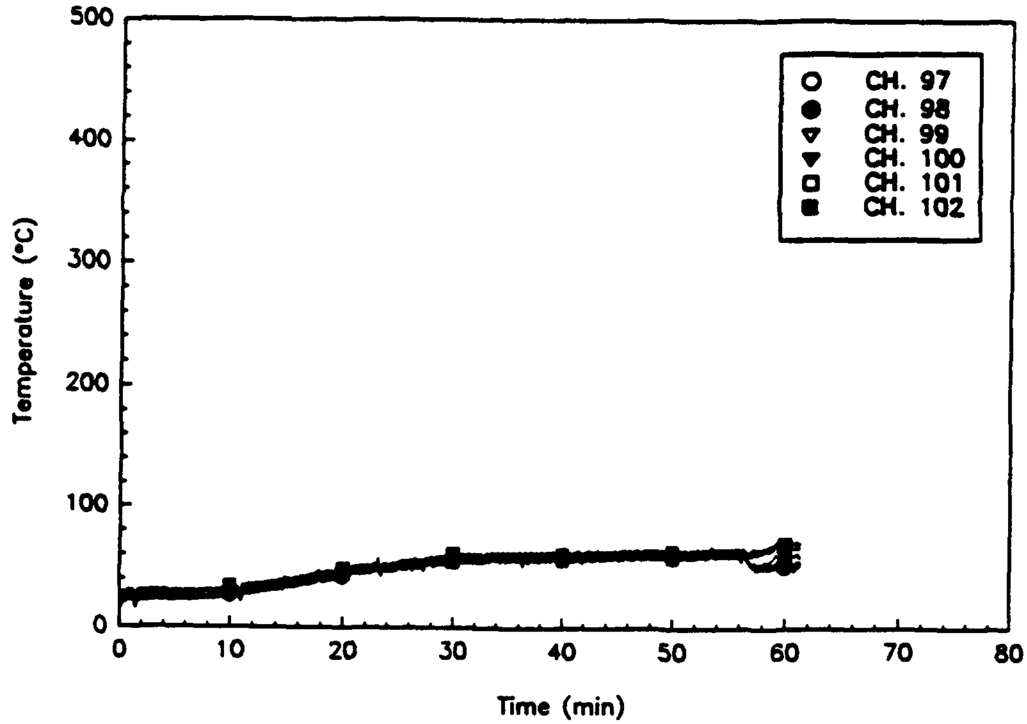

Fig. A201 – CIC air temperature aft, INS_9

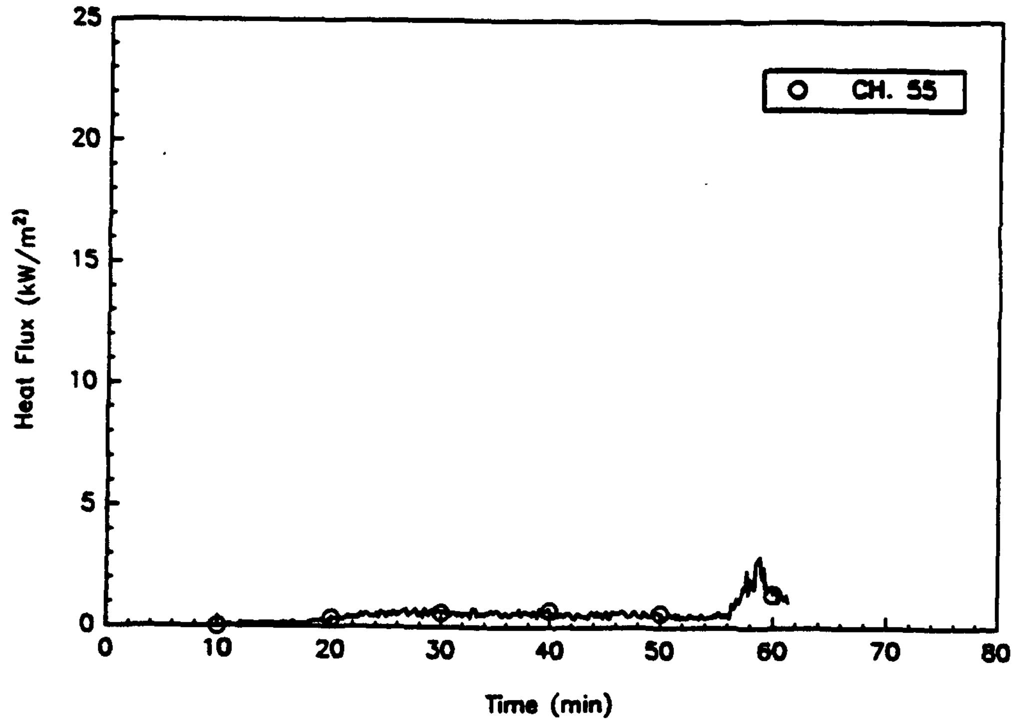

Fig. A202 – Total heat flux at CIC overhead, INS_9

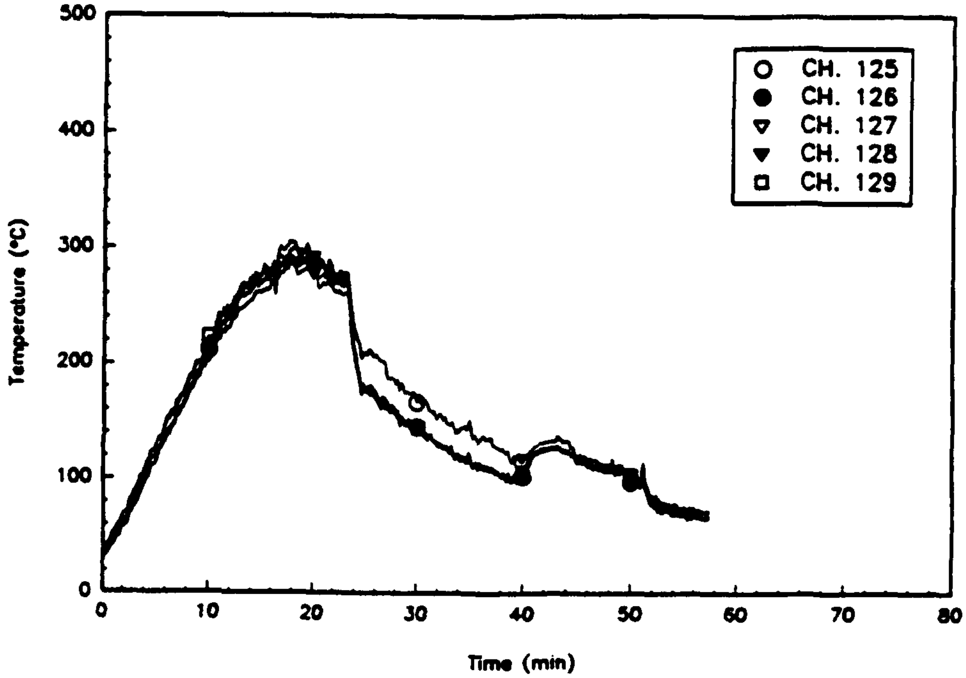

Fig. A203 – RICER 2 air temperature forward, INS_10

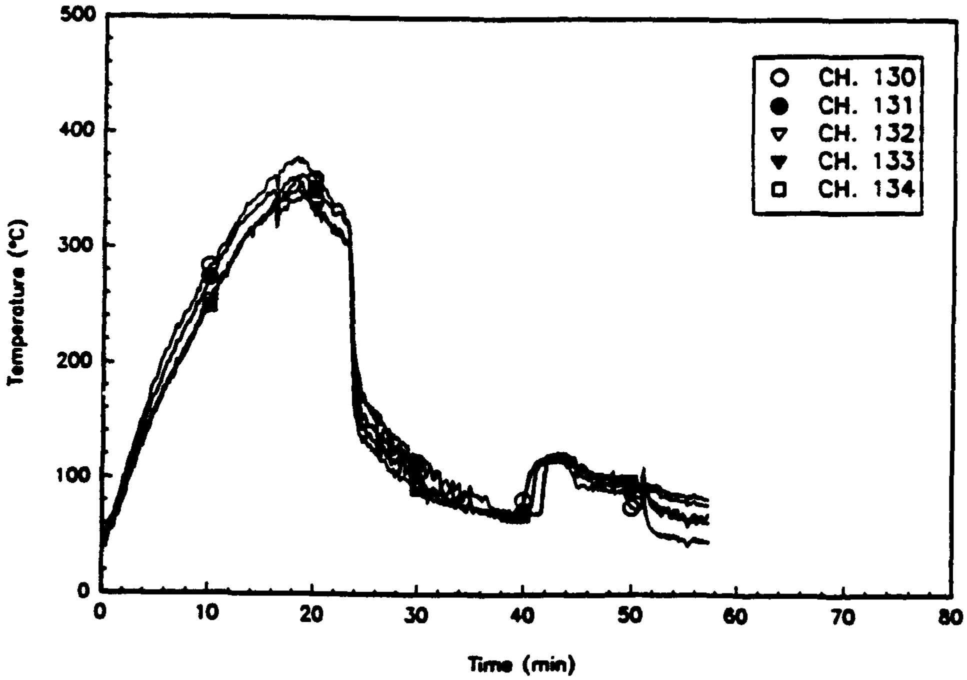

Fig. A204 – RICER 2 air temper e aft, INS_10

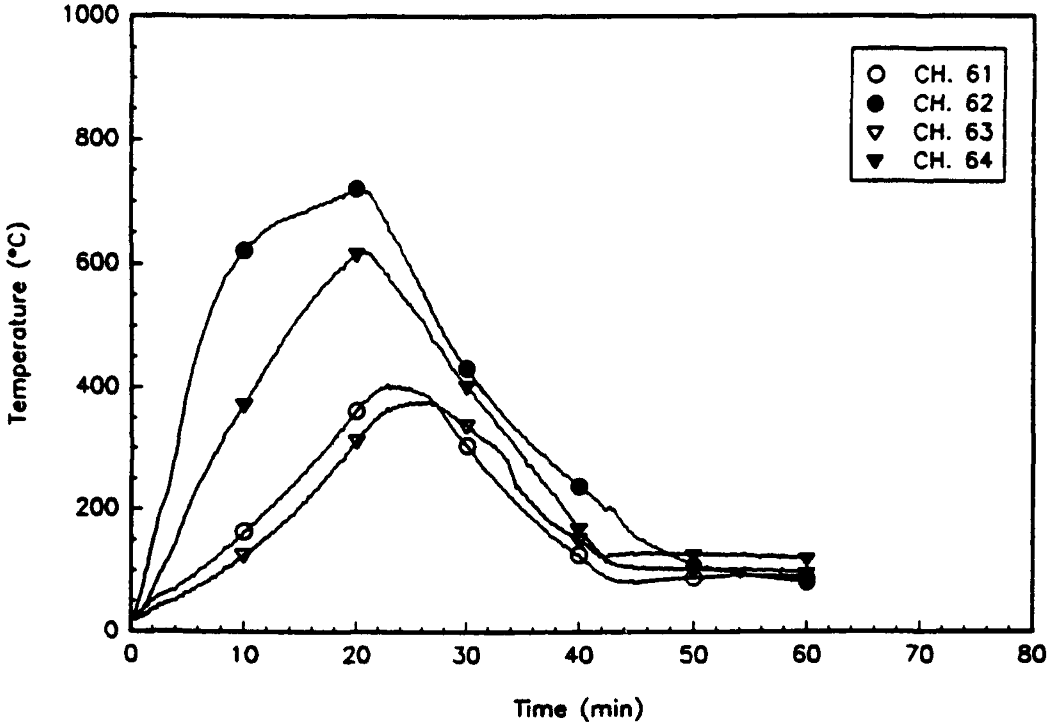

Fig. A205 – RICER 2 deck temperatures aft, INS_10

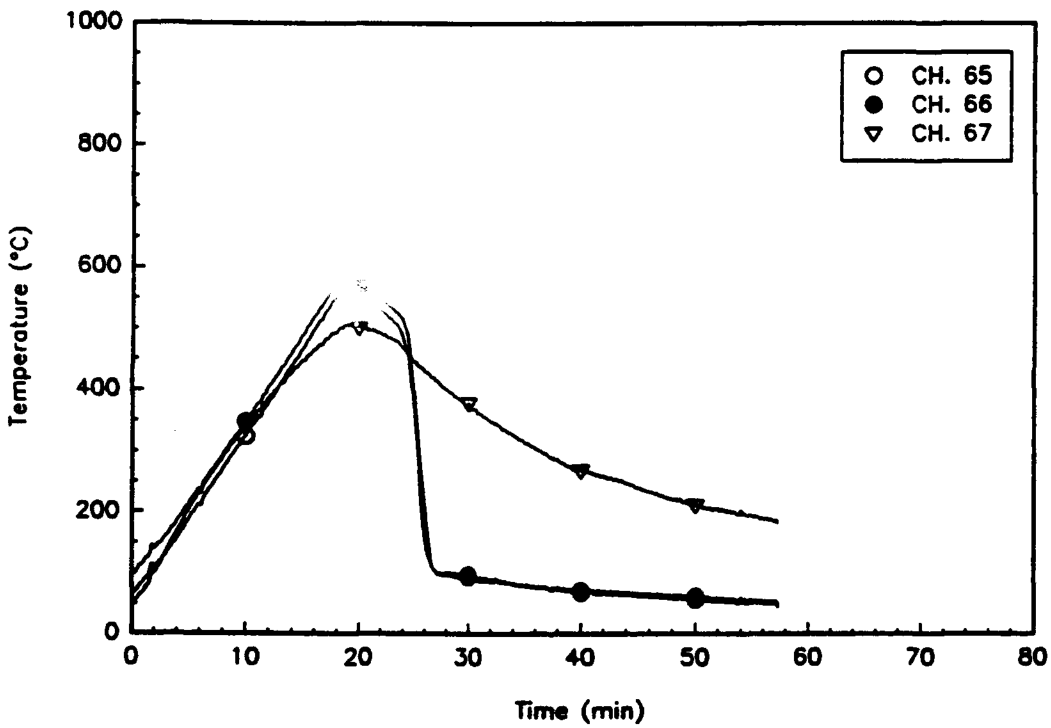

Fig. A206 – RICER 2 deck temperatures forward, INS_10

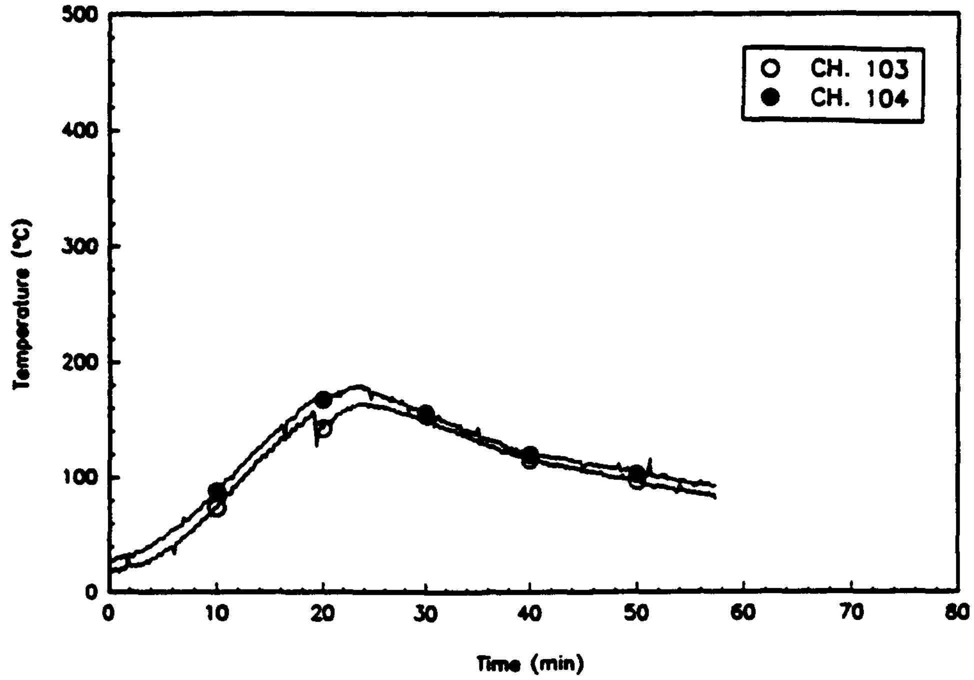

Fig. A207 – FR81 bulkhead temperatures forward, INS_10

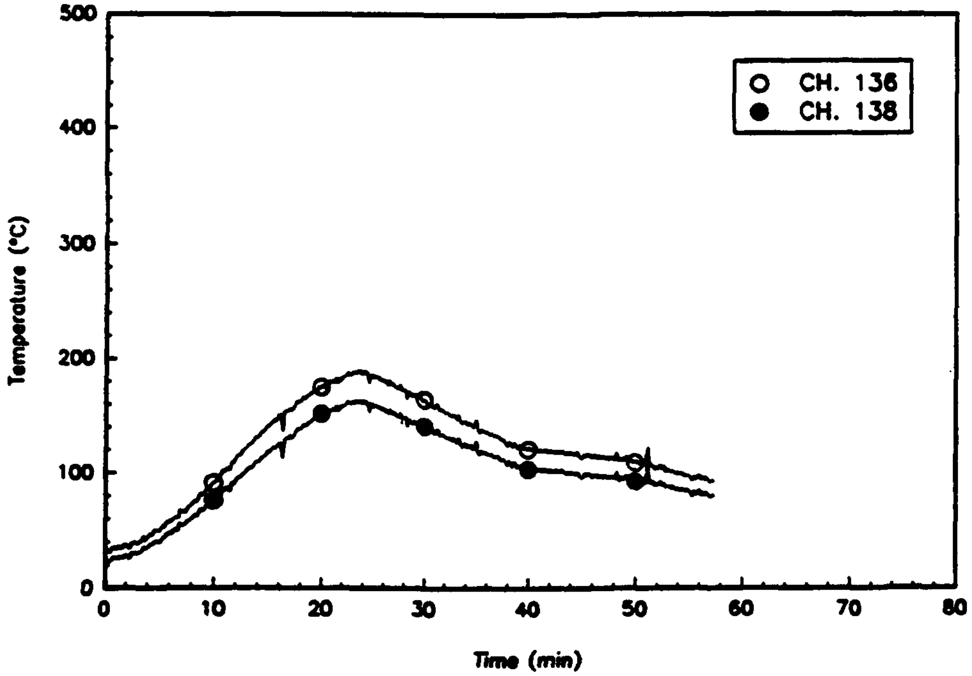

Fig. A208 – FR88 bulkhead temperatures
(RICER 2 side), INS_10

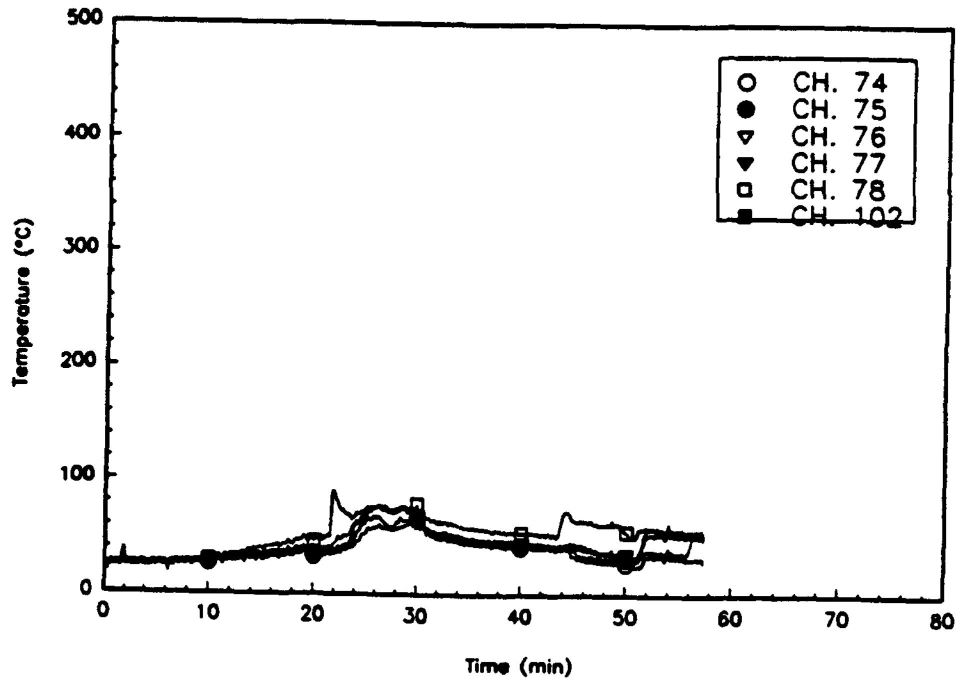

Fig. A209 — RICER 2 air temperature aft, INS_10

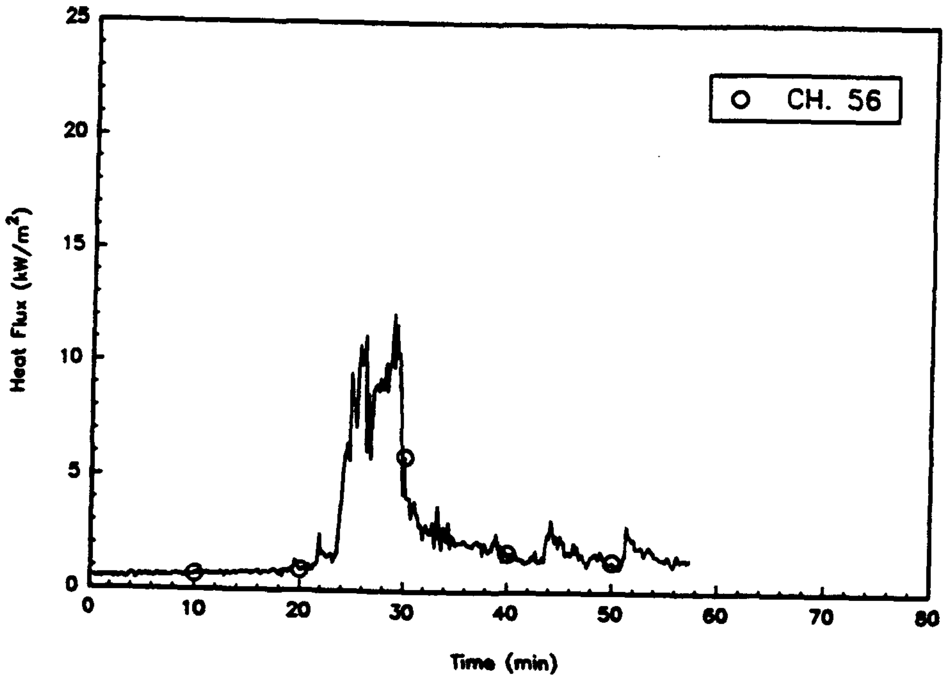

Fig. A210 — Total heat flux at RICER 1 overhead, INS_10

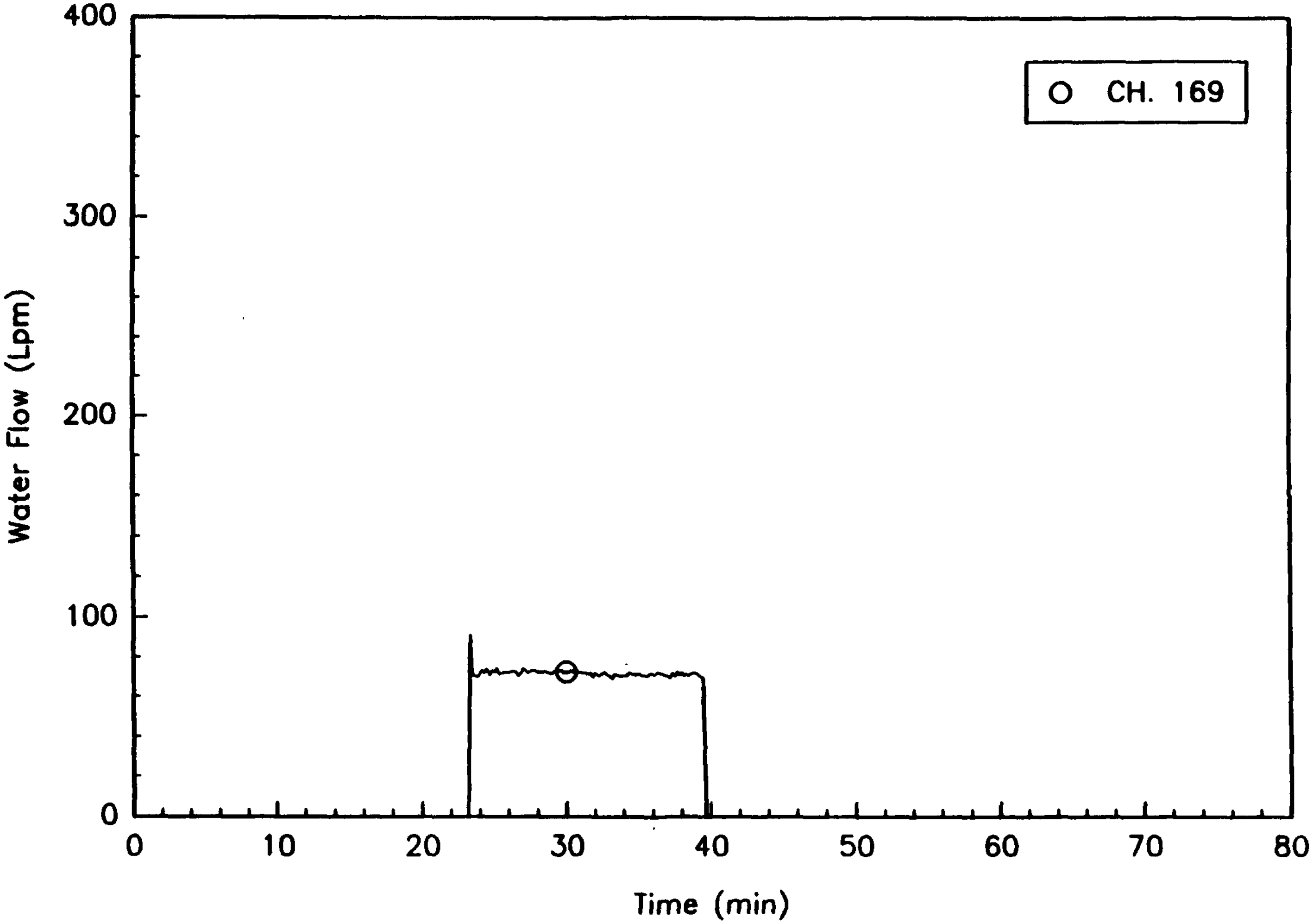

Fig. A211 – Water flow from cooling handline, INS_10

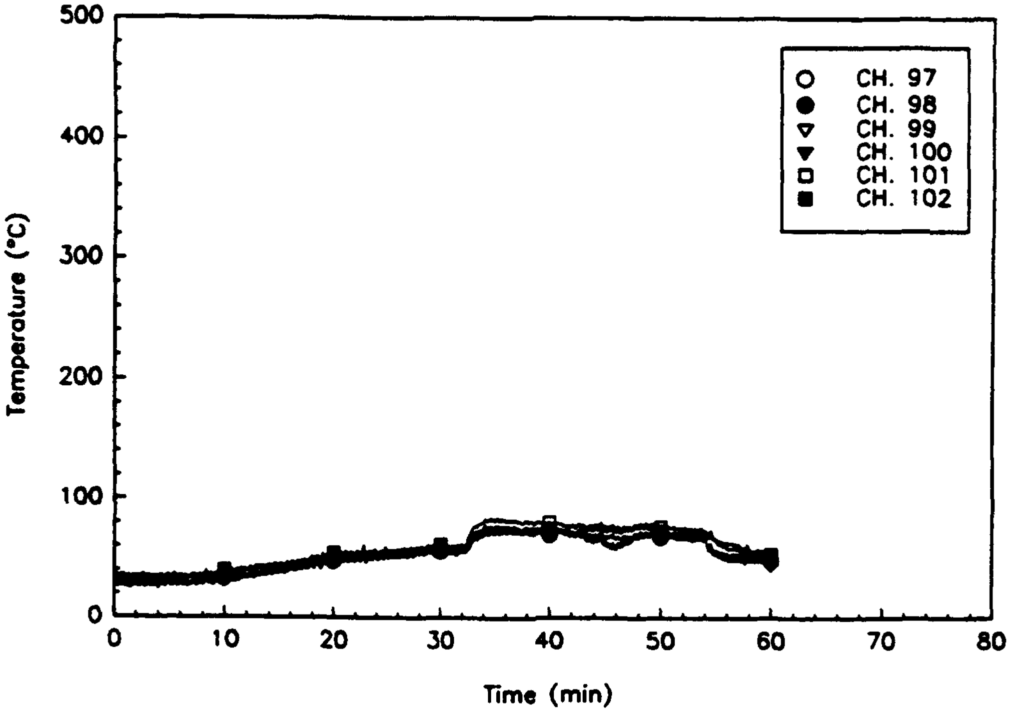

Fig. A212 – CIC air temperature aft, INS_10

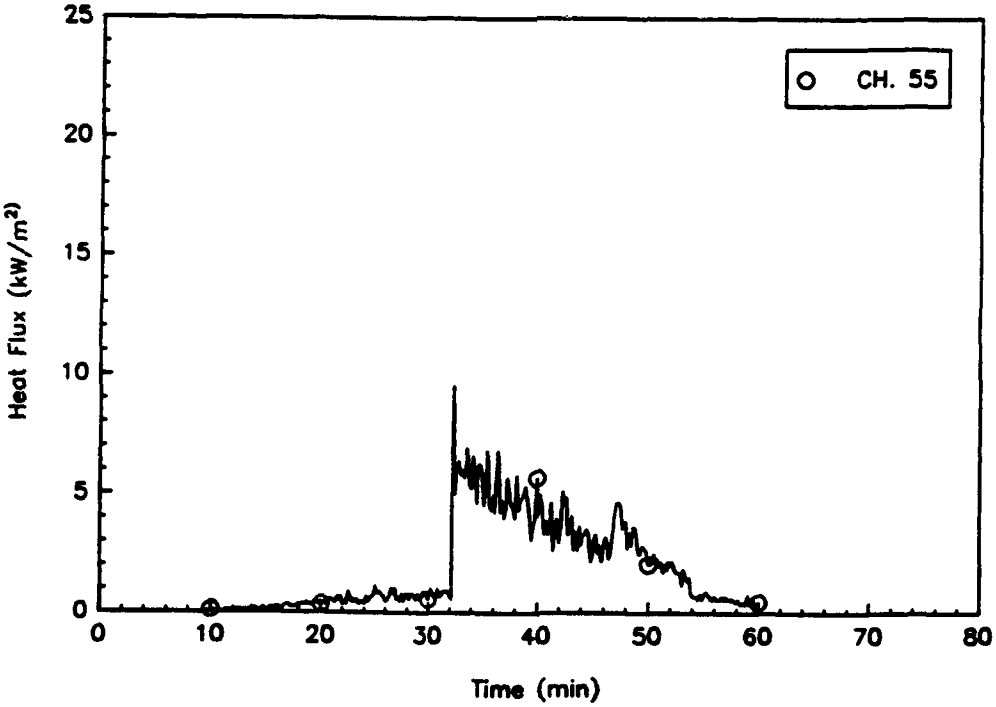

Fig. A213 – Total heat flux at CIC overhead, INS_10